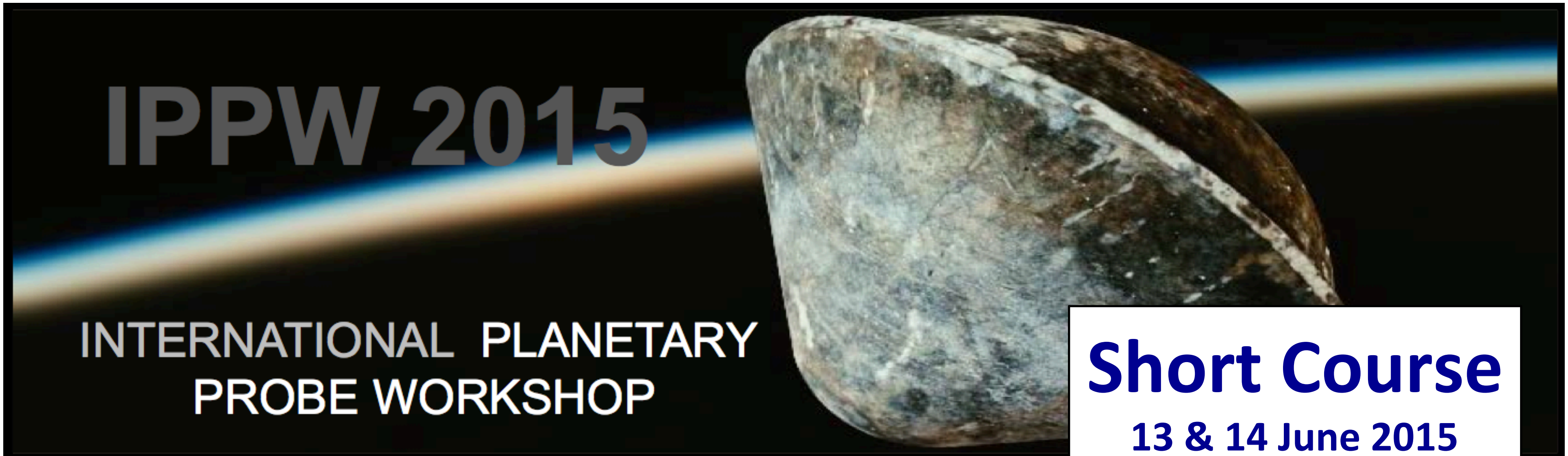

Short Course
13 & 14 June 2015
Cologne, Germany

Basics of Space Communication Systems

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Jet Propulsion Laboratory, California Institute of Technology

Presented by Hannes Griebel

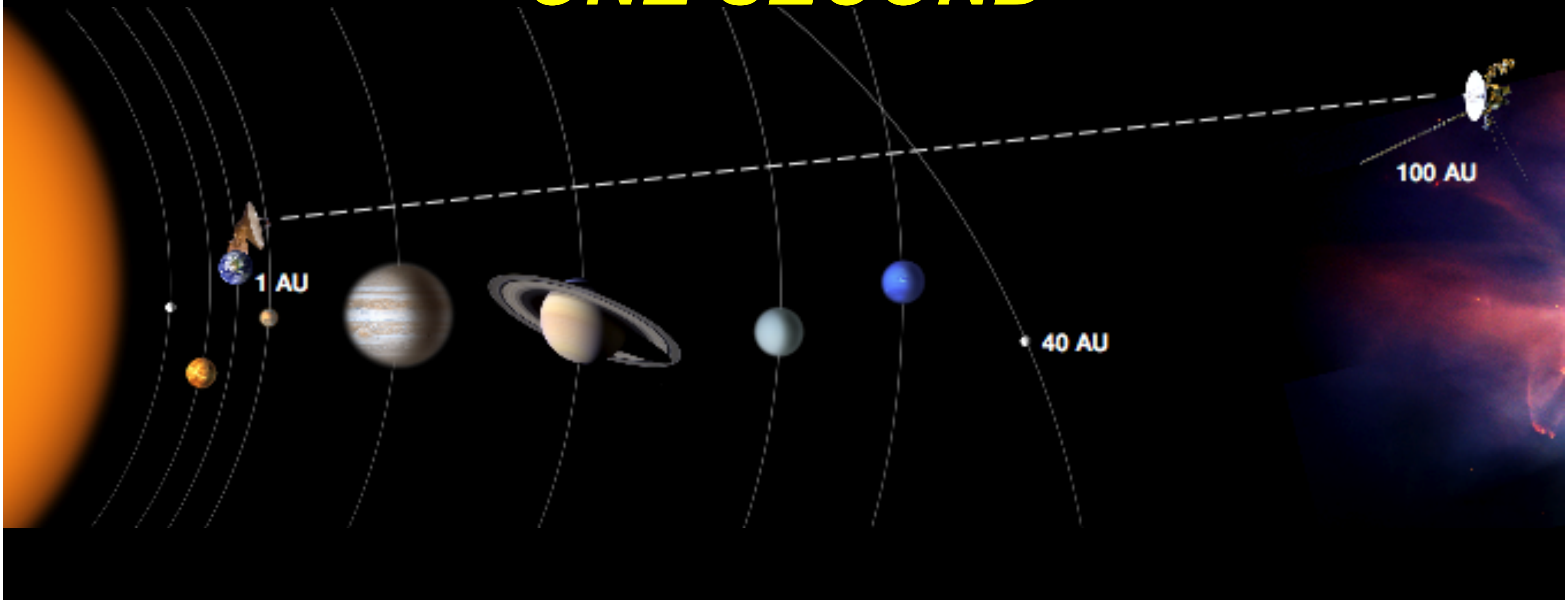
Jet Propulsion Laboratory
California Institute of Technology

Challenge of Deep Space

The Ultimate in Long Distance Communications

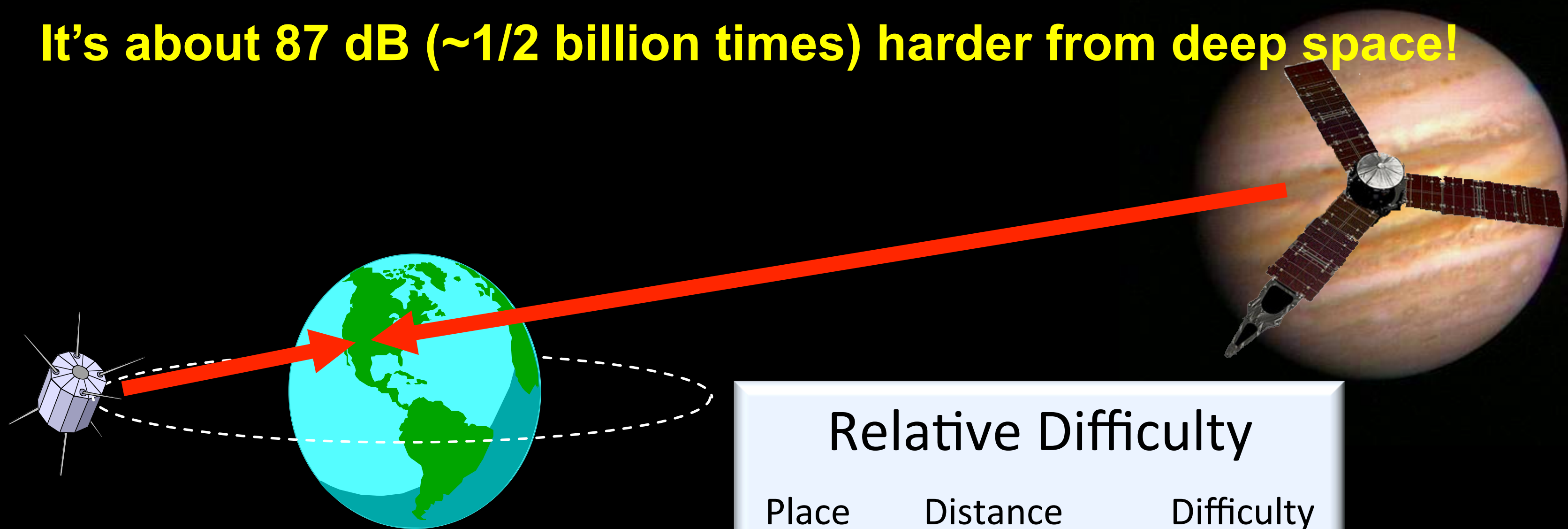
Power received by the 70m DSN antenna from Voyager is so small that if it were to be accumulated for 10 trillion years it can power a refrigerator light bulb for

ONE SECOND



Why is Deep Space Communications Difficult?

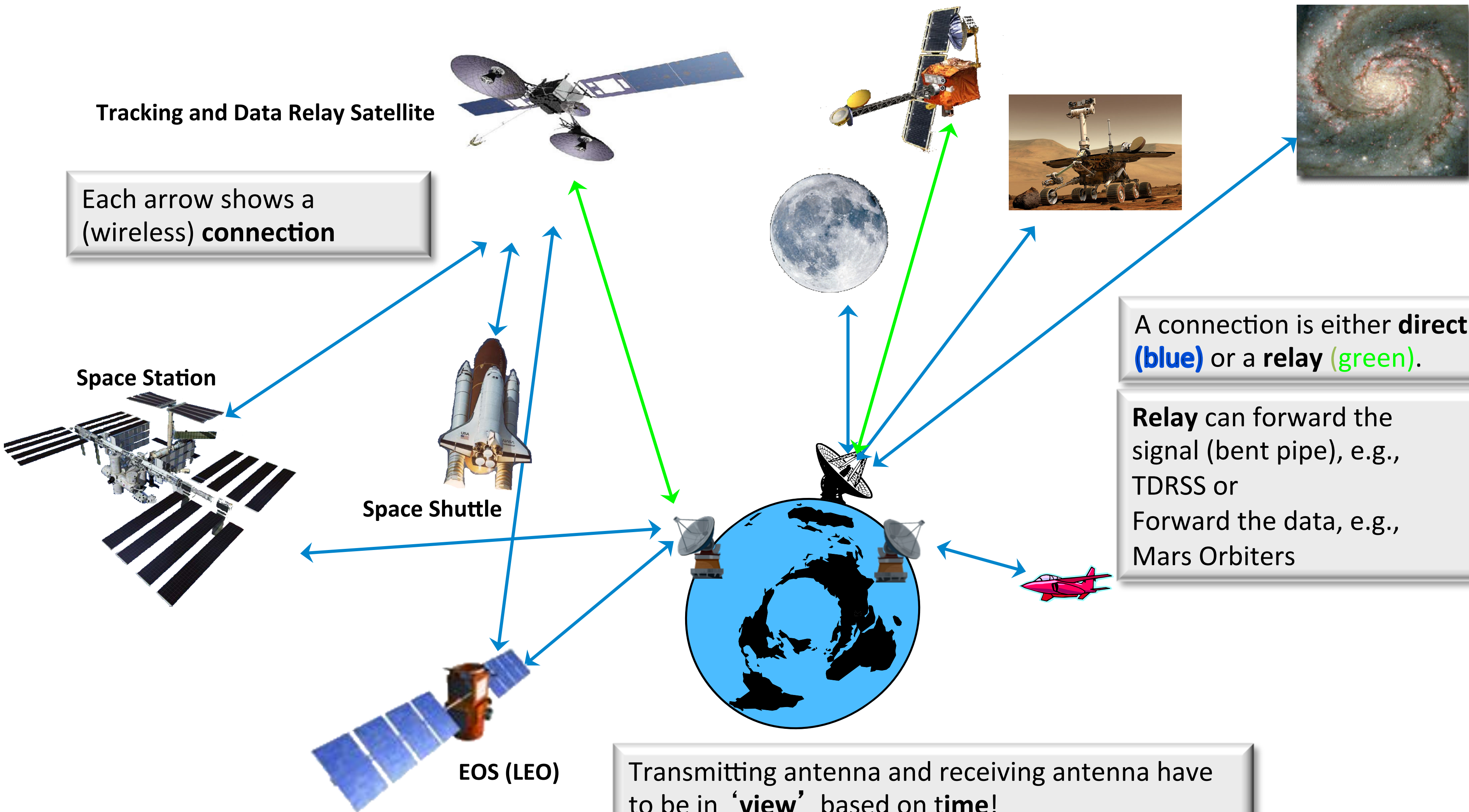
- **Communications performance decreases as the square of the distance**
- **Jupiter is nearly 1 billion km away, while a GEO Earth satellite is about 40 thousand km away**
  - **It's about 87 dB (~1/2 billion times) harder from deep space!**



Relative Difficulty

Place	Distance	Difficulty
Geo	$4x10^4$ km	Baseline
Moon	$4x10^5$ km	100
Mars	$3x10^8$ km	$5.6x10^7$
Jupiter	$8x10^8$ km	$4.0x10^8$
Pluto	$5x10^9$ km	$1.6x10^{10}$

Space Communications Environment



Each arrow shows a (wireless) **connection**

A connection is either **direct (blue)** or a **relay** (green).

Relay can forward the signal (bent pipe), e.g., TDRSS or
Forward the data, e.g., Mars Orbiters

Transmitting antenna and receiving antenna have to be in '**view**' based on **time**!

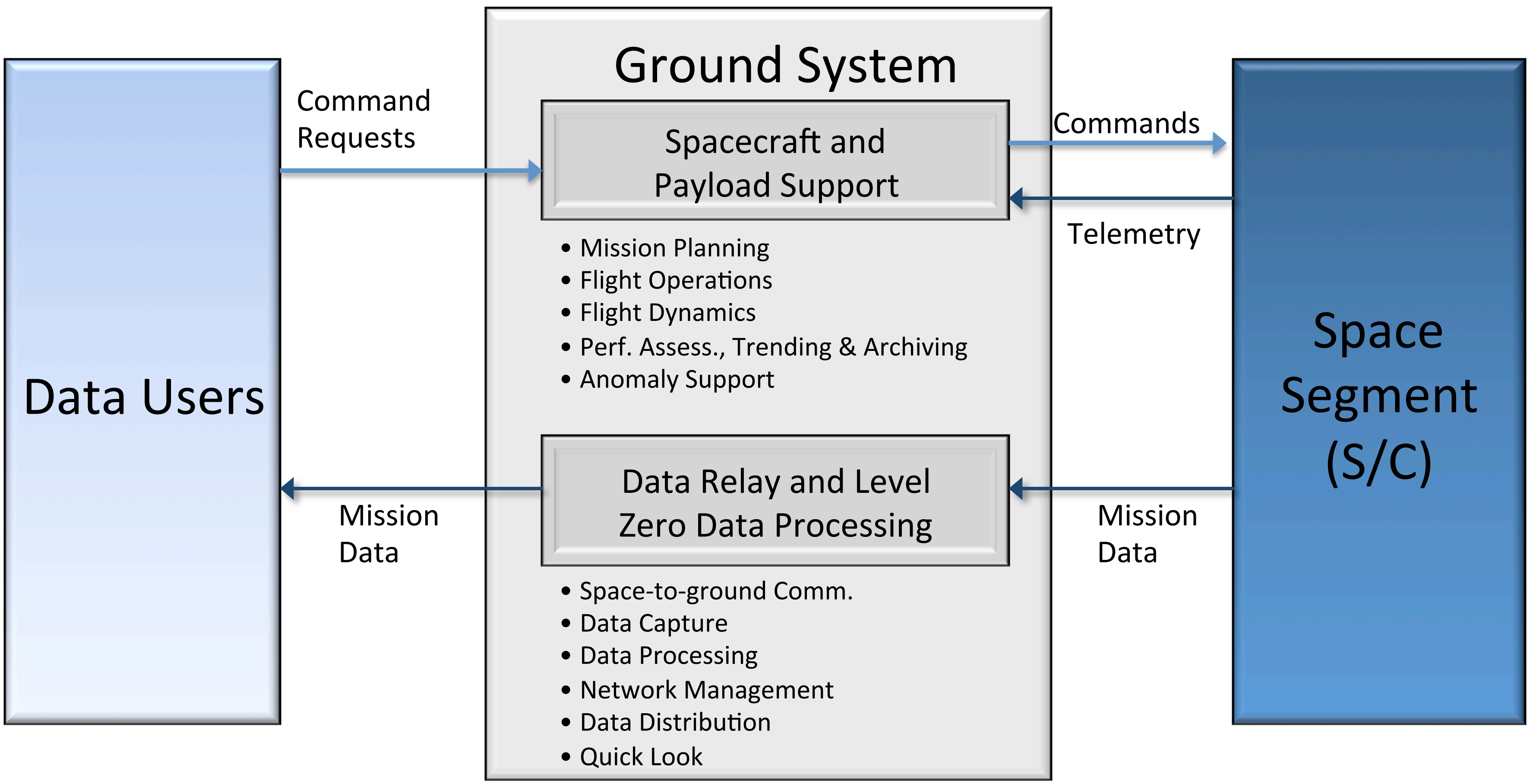
'**View Period**' – the length of contiguous time of a view

Fundamental of Space Communications

- For successful space communication with microwaves you need:
  - **Line of sight** between the space vehicle and the receiver
  - **Ability to point** the antennas at each other
  - **Sufficient received signal power** compared to background noise
    - Large antennas
    - Ultra low noise cooled preamplifiers
    - Large transmitters (ground stations)
  - **Error correcting coding** to improve performance in **noise**
  - **Disruption tolerant protocols** to implement networks in space
  - Integrated **metric tracking** measurements
- **With increased distances these become more important and difficult**

Space Communications Operations 101

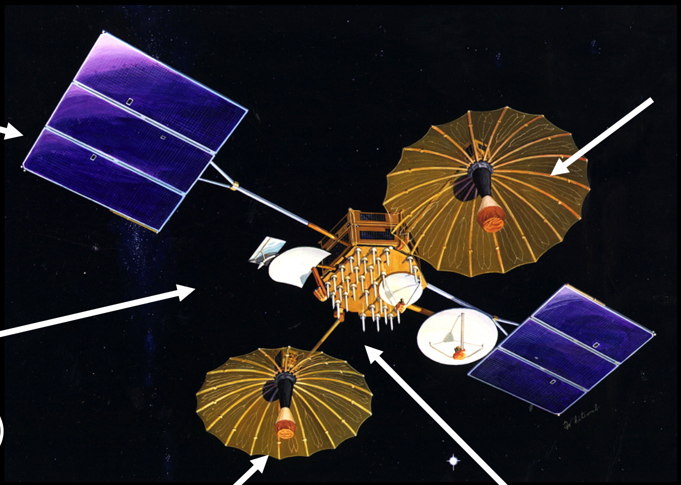
Relation Between Space Segment, Ground System, and Data Users*



* Based on Wertz and Wiley; Space Mission Analysis and Design

Space Segment: Tracking and Data Relay Satellite

Solar array
Power output is approximately 1800 watts



Omni Antenna (S-band) and Solar Sail

Single Access Antenna
Dual frequency communications and tracking functions:

- S-band TDRSS (SSA)
- Ku-band TDRSS (KuSA)
- Ku-band auto-tracking

4.9 meter shaped reflector assembly
SA equipment compartment mounted behind reflector
Two axis gimballing

Space-to-Ground-Link Antenna
TDRS downlink
2.0 meter parabolic reflector
Dual orthogonal linear polarization TDRS:

- single horn feed
- orthomode transducer

Two axis gimballed

Multiple Access Antenna
30 helices:

- 12 diplexers for transmit
- 30 receive body mounted

Single commanded beam, transmit
20 adapted beams for receive
Ground implemented receive function

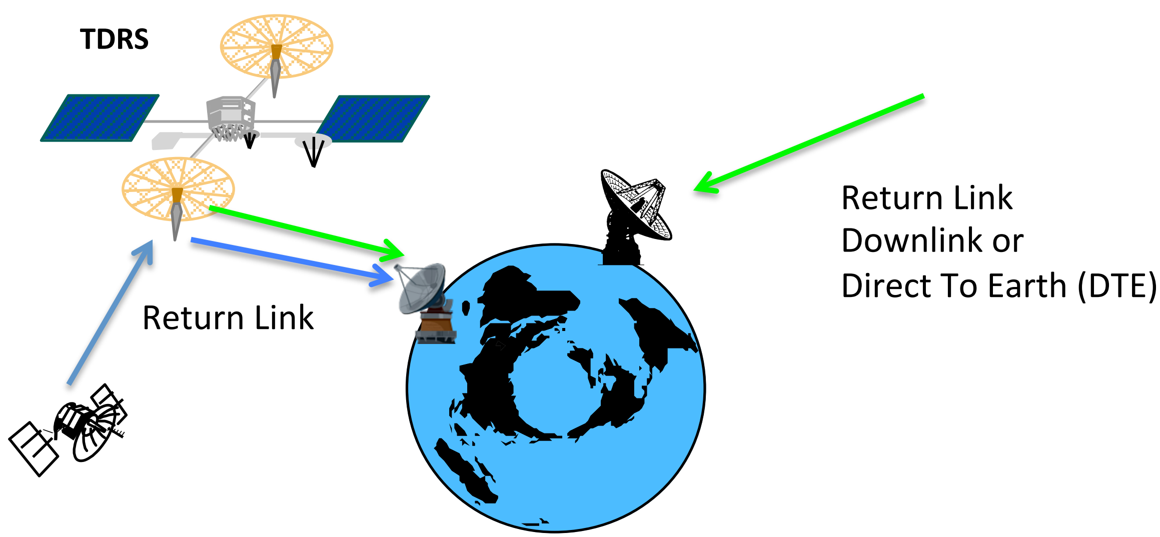
Forward (FWD): link from TDRSS Ground Station through TDRS to Customer Spacecraft
Return (RTN): link from Customer Spacecraft through TDRS to TDRSS Ground Station

Mission Requirements I

- Data **from** spacecraft (s/c) to the mission ground system
- Data **to** s/c from the mission ground system
- Location of s/c, its movement and direction
- Location of mission targets, their movement and direction
- Minimum s/c resources devoted to communications
- Emergency communications
- Technology agility
- Science use of the communication system
  - Radio Science

Mission Requirements II

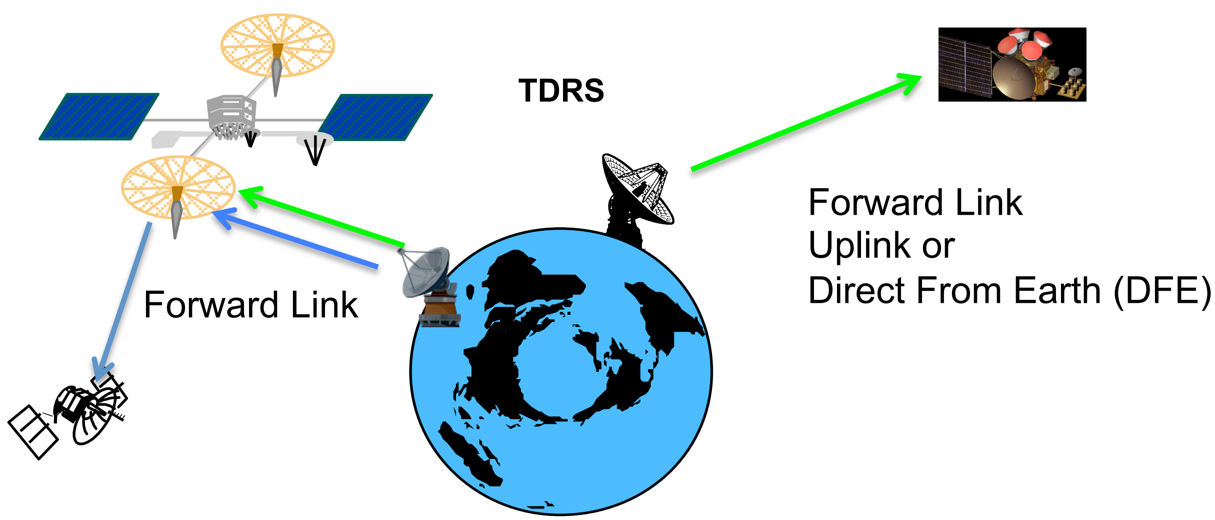
- Get information from the spacecraft (s/c).
  - Data collected by the spacecraft (pictures, sensor data...).
  - Spacecraft information (status, performance...), protocol related information.
- The signal path is called:
  - **Return Link** – s/c to ground (can be through relays).
  - **Downlink or Direct to Earth (DTE)** – Direct connection from s/c to ground.



Telemetry – 'Measurement at a distance' – nowadays refers to non-science data except in deep space communications.

Mission Requirements III

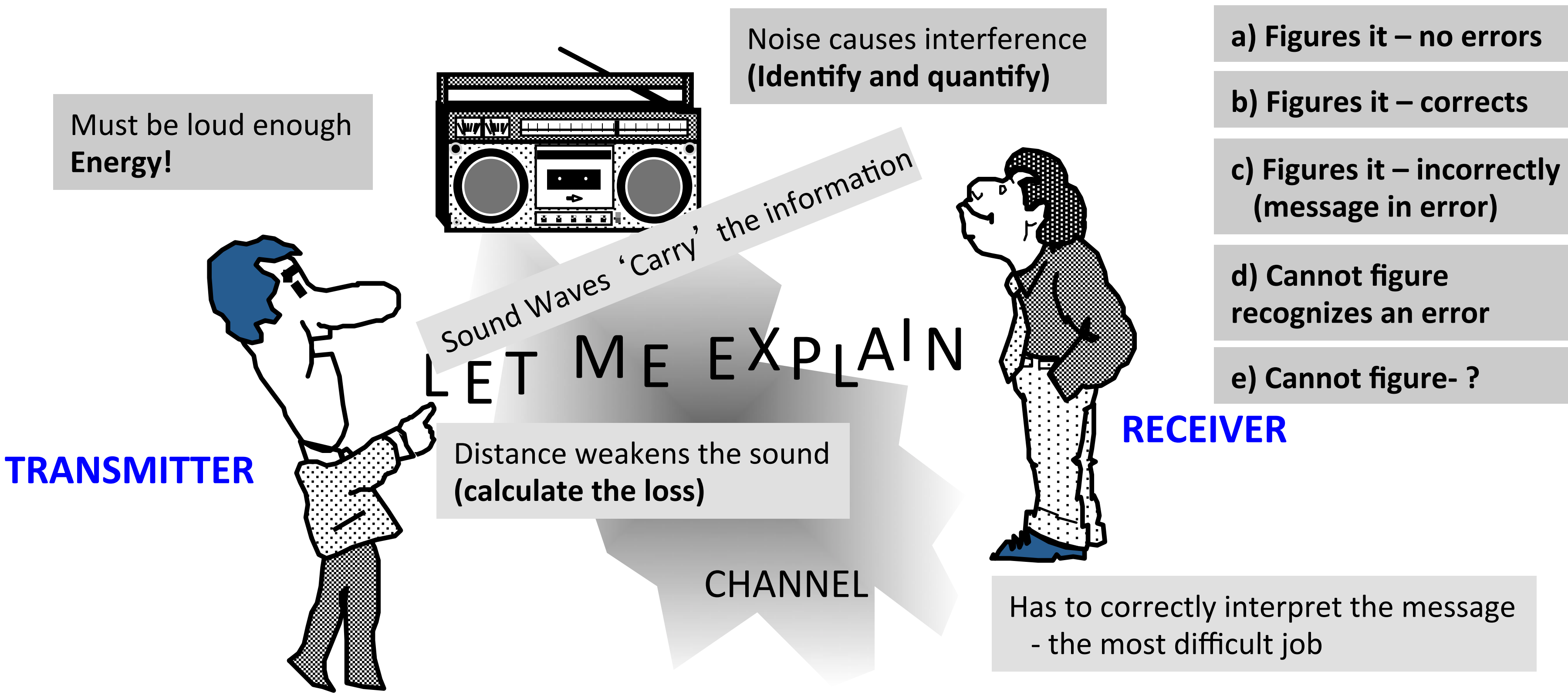
- Send information to the spacecraft.
  - Instructions to perform functions on the s/c (Command).
  - s/c parameters, protocol related information.
  - Software uploads.
- The signal path is called.
  - **Forward Link** - Ground to s/c (can be through relays).
  - **Uplink** or **Direct From Earth (DFE)** or **Commanding** – Direct connection ground to s/c.



Command – Instructions sent to the spacecraft (TDRS commands on uplink).
Sequence – A set of commands with information about when and what to execute.

Communications Theory Basic Concepts

Transmitter and Receiver must use the same language



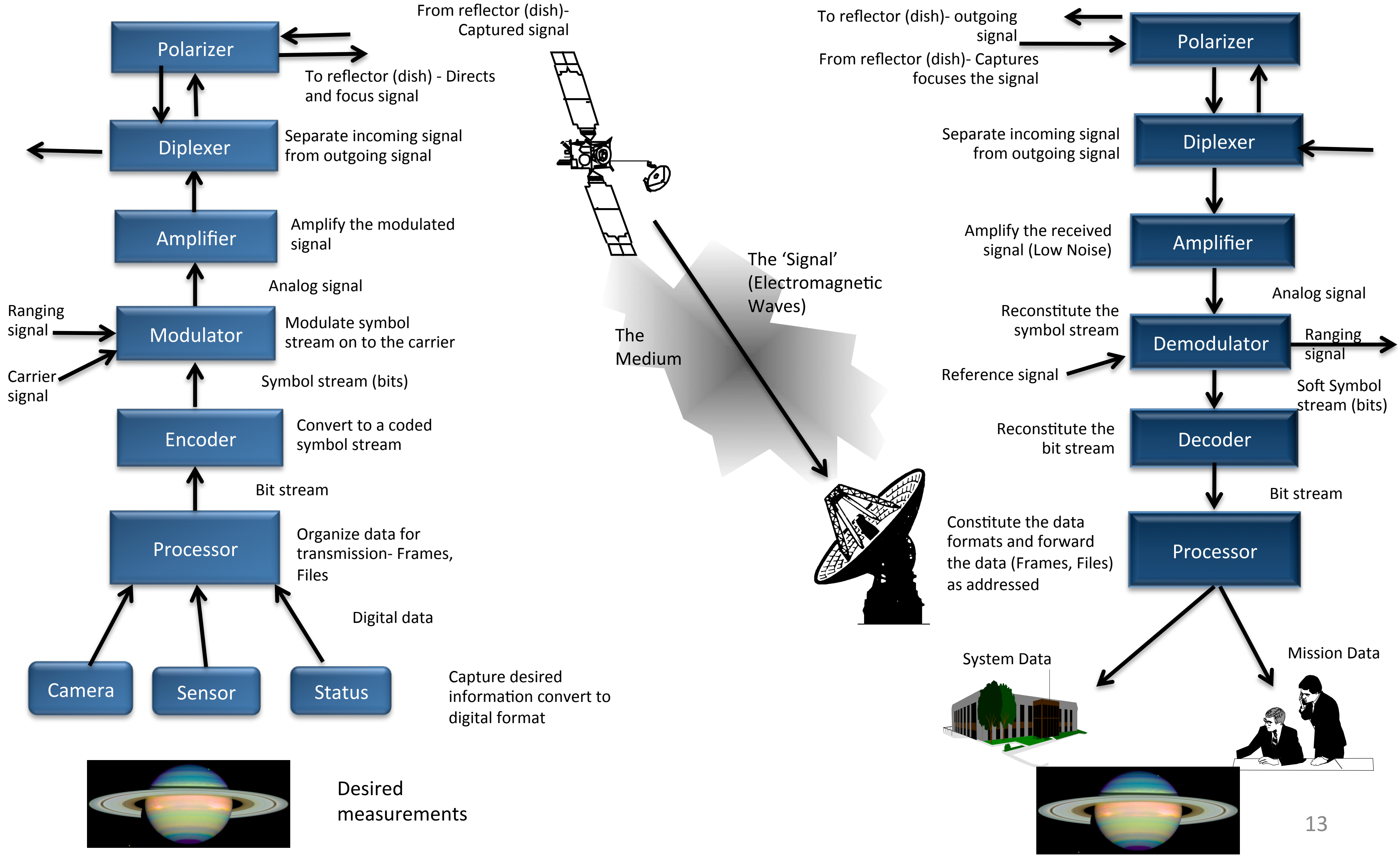
The fundamental problem of communications is that of reproducing at one point either exactly or ***approximately*** *a message selected at another point.*

Claude Shannon

Key Concepts

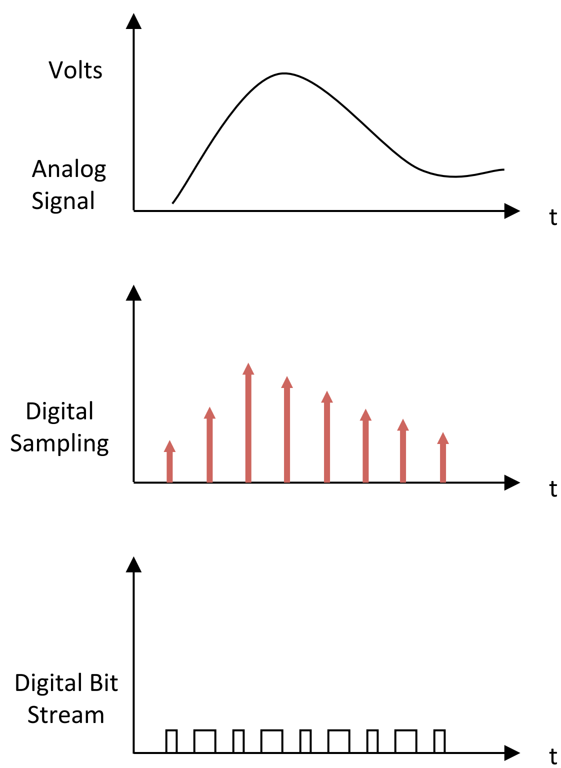
- The receiver (human) can **reasonably interpret** the **message** based on the '**loudness**' compared to any other sound
  - The unit of information is a **word**
  - The message is carried over sound **waves**
- **Digital telecommunications work in an analogous manner:**
  - The receiver can **estimate** the **information** based on the **power** in the signal in relation to the **noise**
  - The unit of information is a **bit**
  - The message is carried over electromagnetic **waves**
- System design accounts for **power** from the transmitter to the receiver in a table with elements that add or subtract power, called the **link budget,** accounted in **deciBels (dB)**
  - The **dB** is a ratio of two measured values

Space Communications End to End



Analog and Digital Data

- Why use digital data
  - \+ Better performance vs. noise
  - \+ Lends itself to computer processing and coding
  - \- Consumes more bandwidth

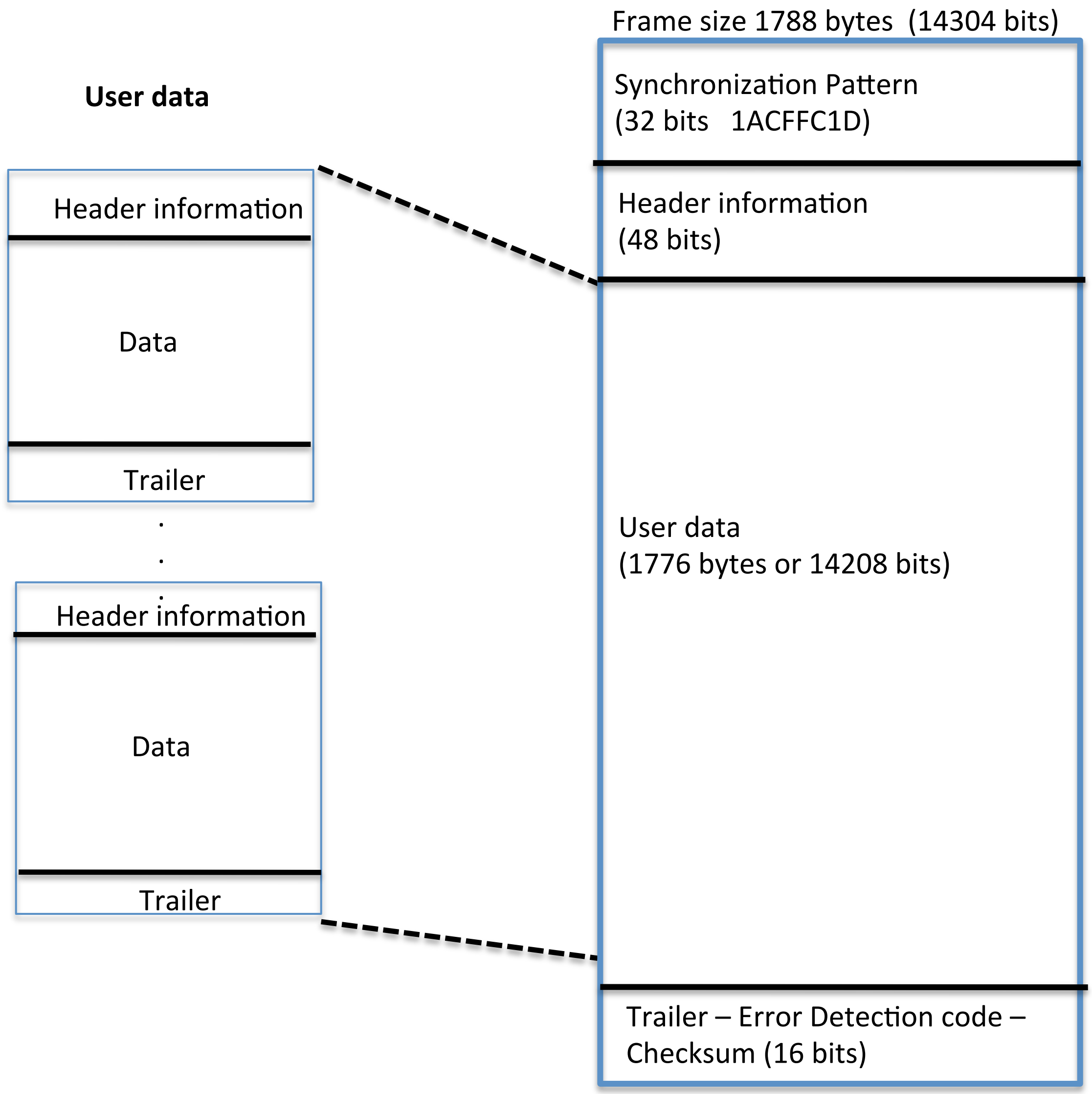


Sampling Rate ≥ Nyquist rate (≥ 2 f_{max})

f_{max} – max frequency component of the original signal

Blocks, Packets, and Frames

00011010110011111111110000011101110100111000111010100111100101O…………… The system sees a string of 1's and 0's organized as



Allows the system to recognize the start of a – block/ packet/ frame

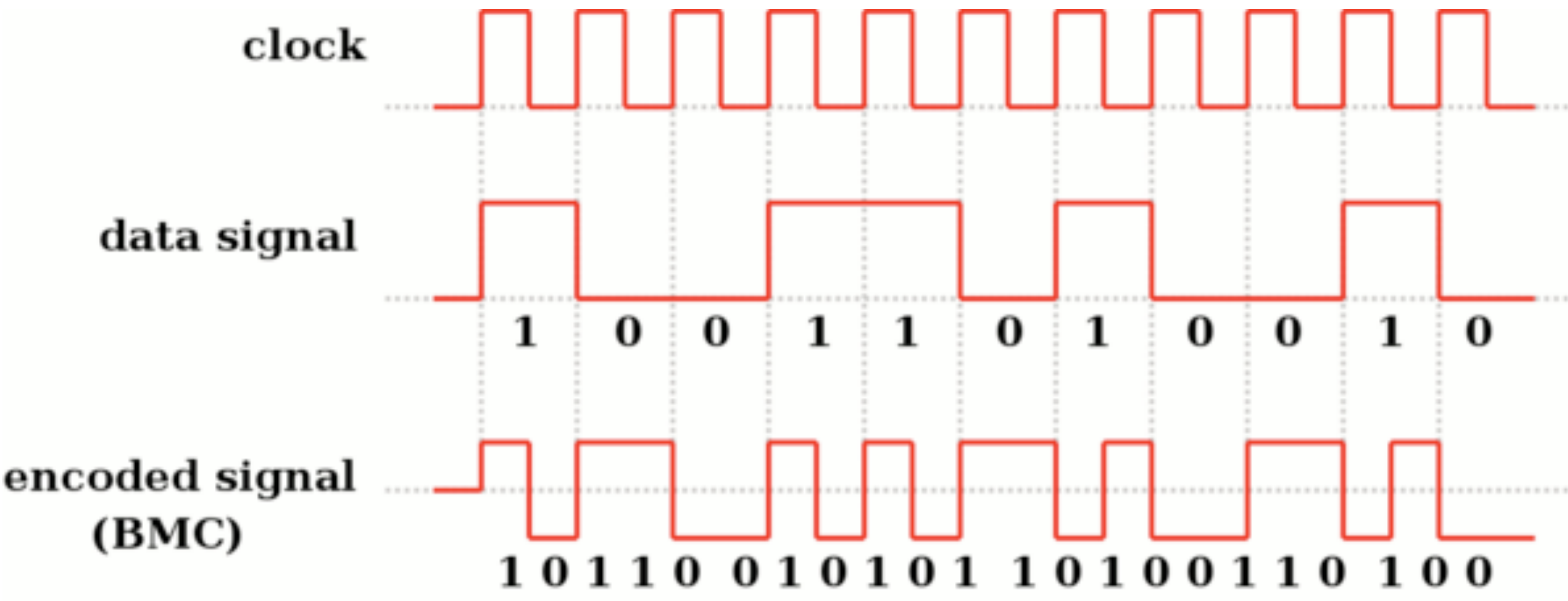
Describes information about the block such as - source, destination, type of data, number in a sequence, size, original or retransmitted, etc

May have a single or multiple user data

Information that allows the receiver to ensure that there is no corruption in the block

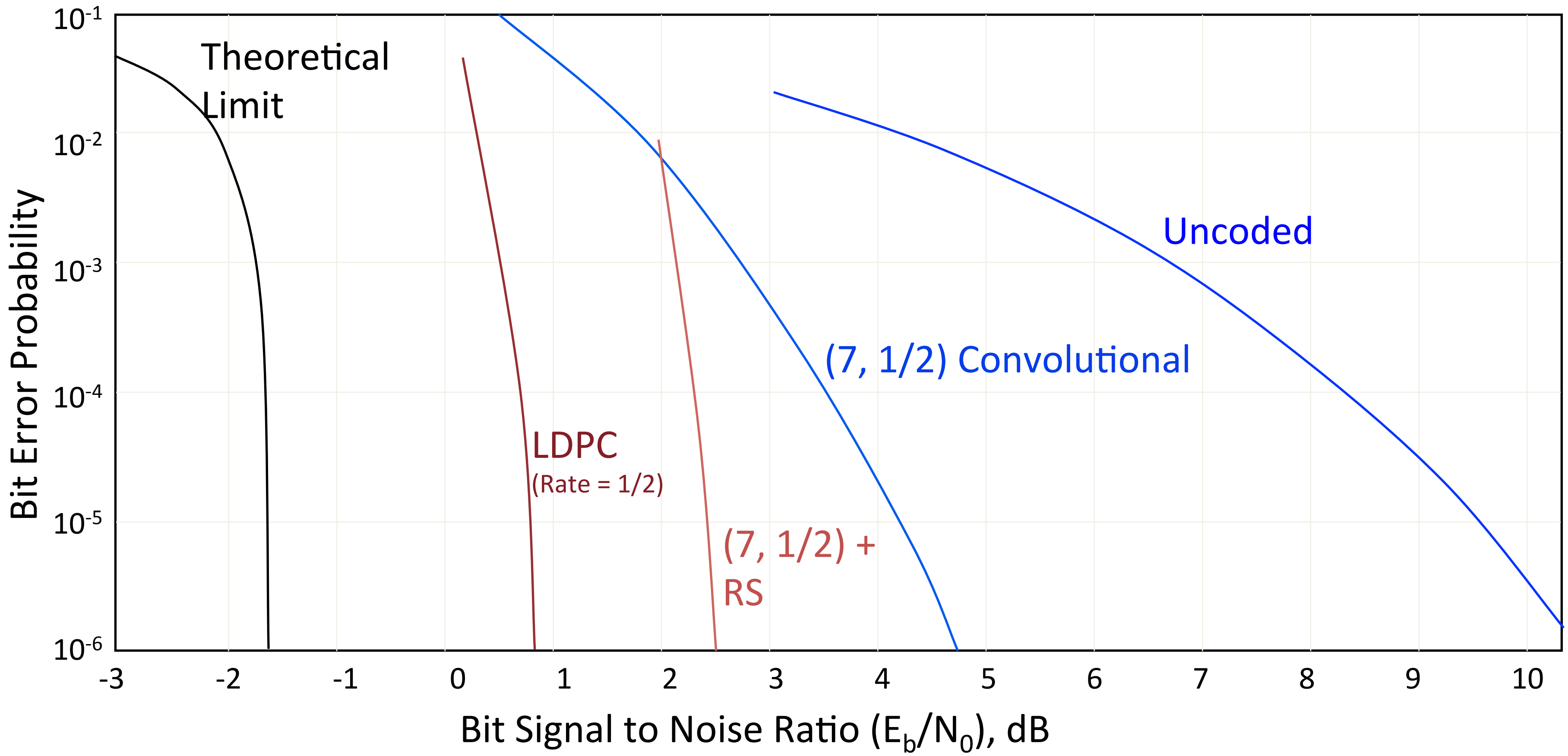
Coding

Coding: The technique of adding additional information (redundancy) to the information stream to allow the receiver to correct incorrect interpretations.



Error Correcting codes allows the receiver to ‘correct’ errors in the estimated received bit stream.

Benefit of Coding on Performance

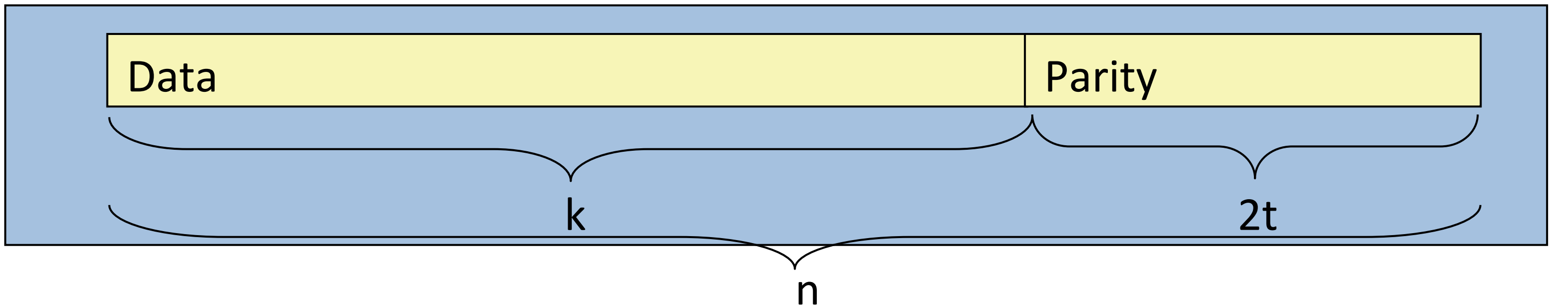


Convolutional coding requires minimal hardware on the spacecraft. When errors occur, they occur in bursts. Adding Reed Solomon (RS) code (block code) improves this performance.

Convolutional Encoding

- As opposed to Reed Solomon encoding which is suited for handling burst transmission disturbances, convolutional encoding is suited for handling a more constant level of background noise threatening to degrade the signal reception.
- The two parameters used to describe a convolutional encoding scheme are:
  - **Code Rate (k/n)**: The ratio of the number of bits into the encoder (k) to the number of channel symbols output by the encoder in a given encoder cycle (n).
  - **Constraint Length (K)**: Identifies the number of k-bit groups fed into the encoder during each cycle.
- A typical convolutional encoder has a Code Rate of ½ and a Constraint Length of K=7.
  - The tradeoff is that the bandwidth must be sized to handle the doubling of the symbol rate when the encoding is applied (Code Rate = ½ means that there are two output symbols for each input bit).
  - Reduction in data errors after decoding typically provides a 5dB Encoding Gain while the doubling of the bandwidth results in a 3dB loss – resulting in a net gain of 2dB.
- Viterbi decoding is the most popular decoding scheme used.
- Reed Solomon and Convolutional encoding are sometimes concatenated together to get the advantages of both coding schemes.

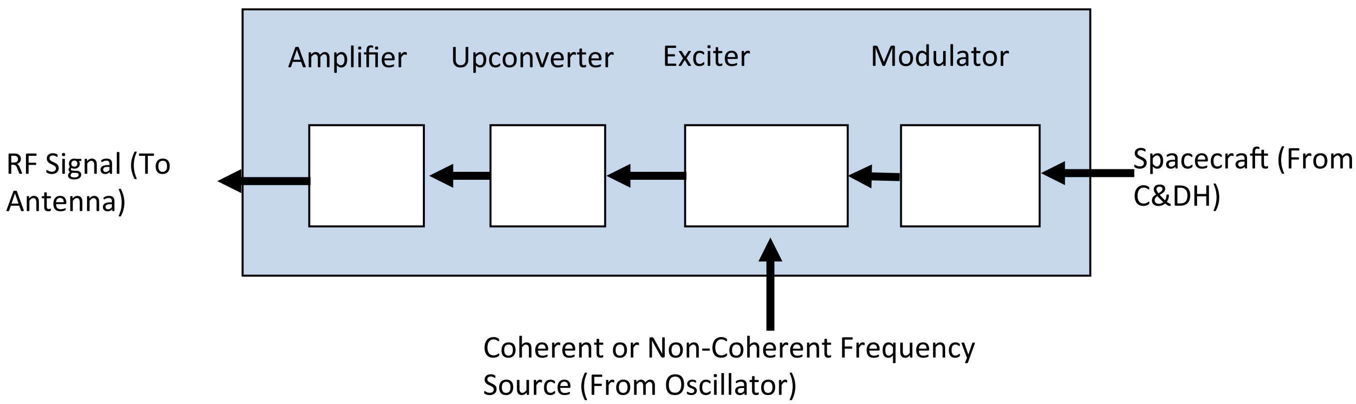
Reed Solomon (RS) Encoding



- This encoding scheme takes a quantity of data symbols (k), each of a given symbol size (s) from the bit stream and appends a number of parity bits (2t) onto the data to form code words of a standard length (n).
- A RS decoder decodes the code word and corrects errors up to "t" symbols per code word. One symbol error can range from 1 bit error in a symbol through all bits in error in a symbol.
- Reed Solomon codes are particularly well suited for correcting burst errors where a series of bits in a code word are received (interpreted) in error.
- Reed Solomon codes are usually represented as RS(n,k) with s-bit symbols.
  - For example, a popular Reed Solomon code is RS(255,223) with 8-bit symbols.
    - Each code word contains 255 code word bytes (2,040 bits)of which 223 bytes (1,784 bits) are data and 32 bytes (256 bits) are parity.
    - The decoder can correct any 16 byte error found in the code word.

Modulator

- A typical transmitter includes the following components:

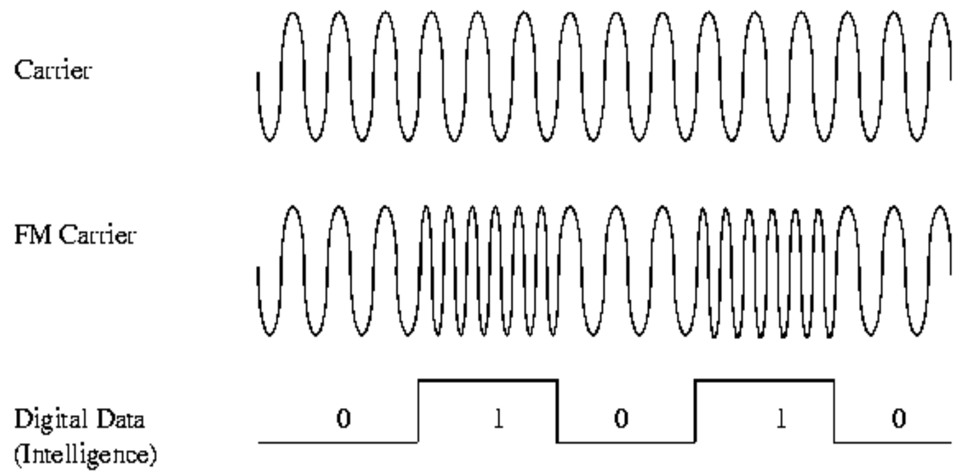


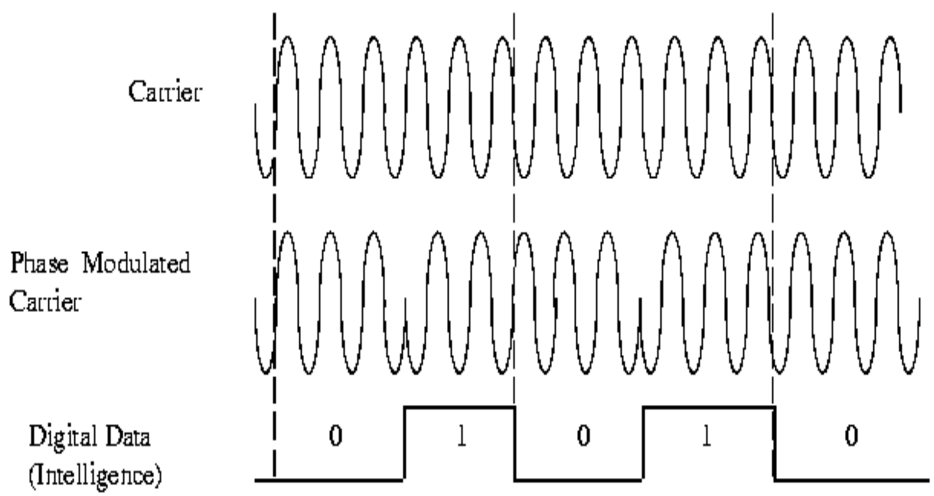
- The modulator receives spacecraft data for the return link from the C&DH subsystem and places this data onto a high frequency RF carrier (through the modulation process described next).
- Often there are signal conditioners which pre-condition the spacecraft data prior to placing it on the carrier; these conditioners may either be part of the RF subsystem or part of the C&DH subsystem.

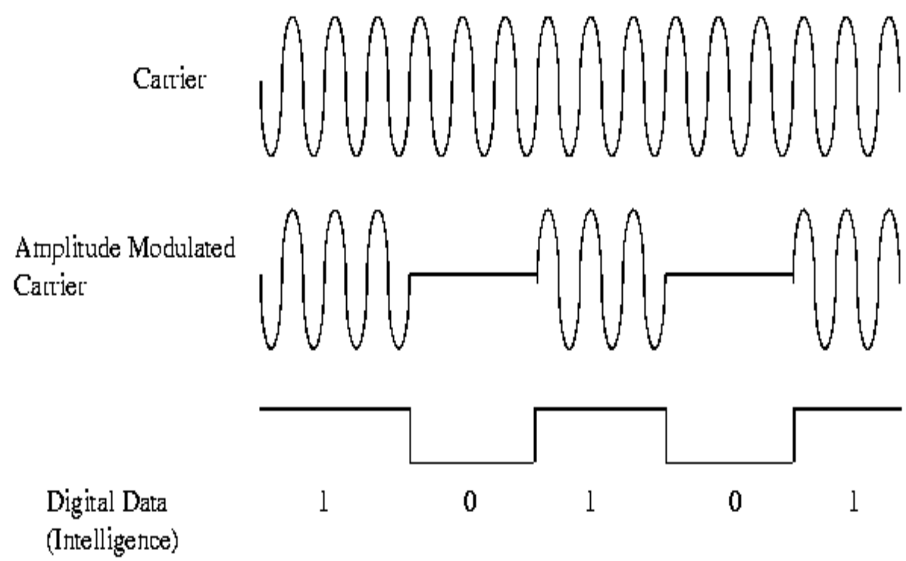
Modulation & Demodulation in Time Domain

Modulation: To change something.
In our case changing some characteristic (such as Frequency, phase or amplitude) of a 'carrier' with information we want to send.

Demodulation: To remove the effects of modulation and recover the information in the signal.

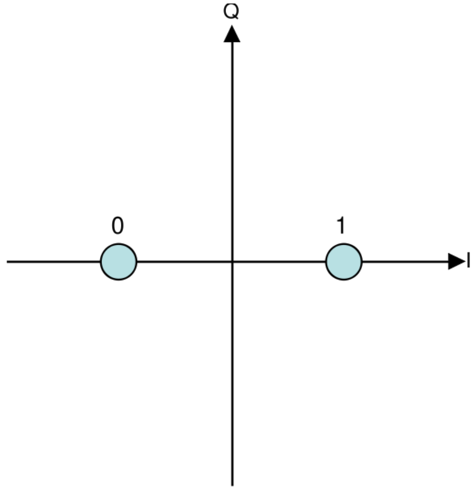


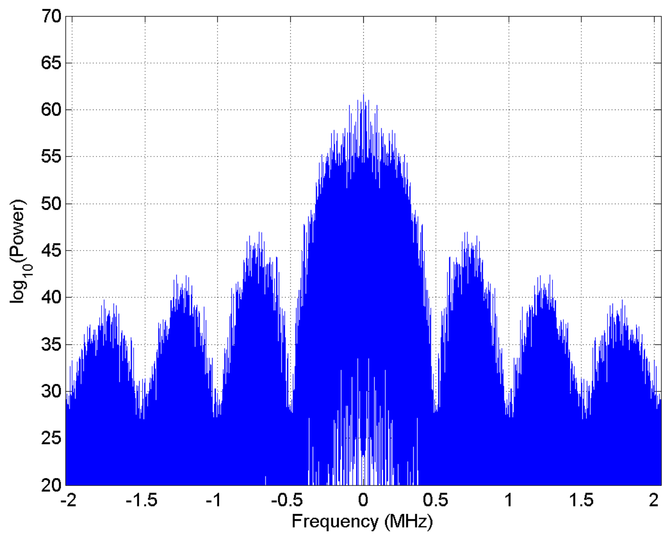




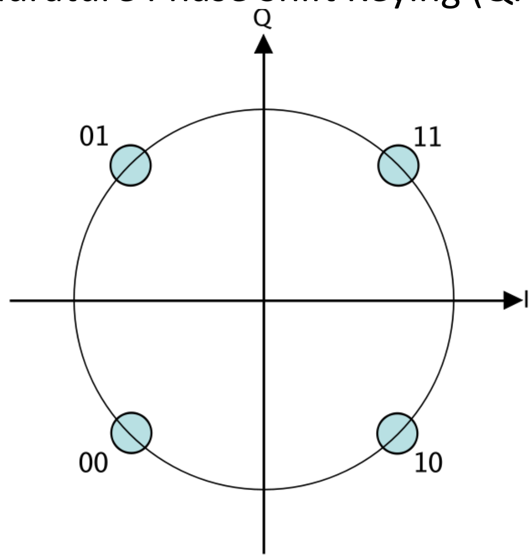
Digital Modulation in Frequency Domain

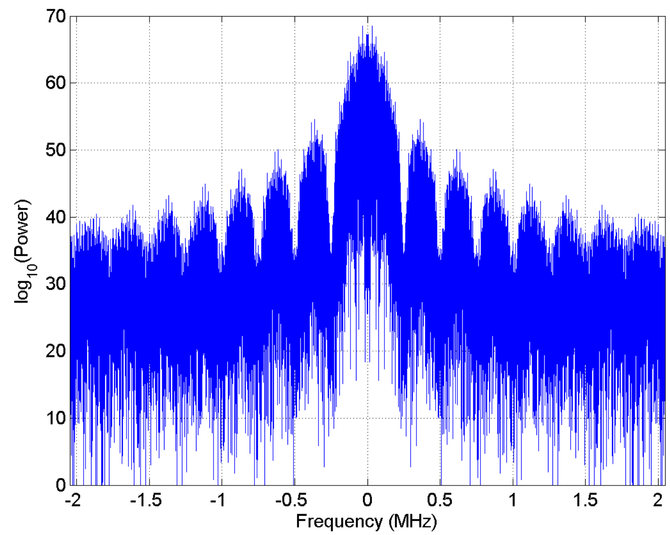
Bi-Phase Shift Keying (BPSK)





Quadrature Phase Shift Keying (QPSK)





Modulation Spread Spectrum

- TDRS "Multiple Access" allows multiple users to use the same band at same time
- Each user's data occupies different parts of the spectrum within the bandwidth
- Two methods:
  - Direct Sequence Code Division Multiple Access (DS-CDMA)
    - Each user assigned unique binary sequence code that is faster than the data
    - Combining (multiplying) these produces a pattern that appears as noise unless you have the code to demodulate (recover the information)
  - Frequency Hopping
    - Implemented in the time domain, both transmitter and receiver have to be synchronized in time and the sequence of frequencies used have to be known
    - The transmitter puts the information on different selected frequencies at a high speed
- Why do this? Better use of spectrum (more users), prevents jamming (signal covers a wide band), prevents interception – the signal looks like noise

FSK Modulation

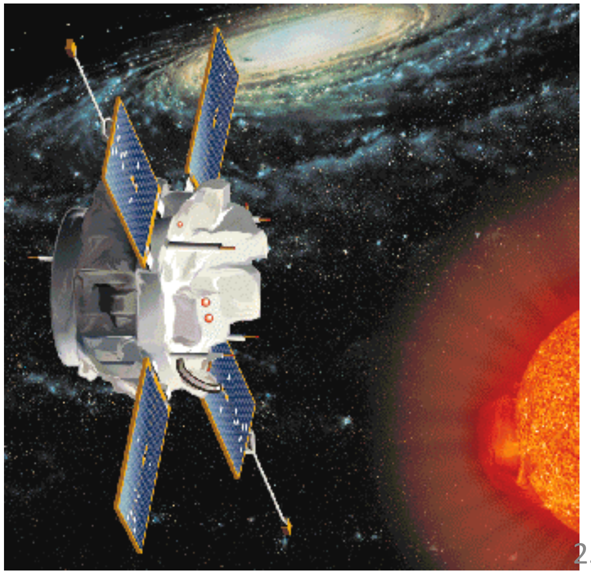
- In Frequency Shift Keying (FSK), a form of FM, carrier frequency is toggled (keyed) between two different frequencies based on the state of the modulating bit (binary 0 or 1)
- This can be extended to multiple frequencies in a modulation scheme known as Multiple Frequency Shift Keying (MFSK), where "M" is the number of possible frequencies of the input carrier. For example, in an 8FSK system, three inputs bits combine in such a way as to shift the carrier frequency to one of 8 possible frequencies.

Geosynchronous MILSTAR communications satellites use MFSK modulation

PSK Modulation

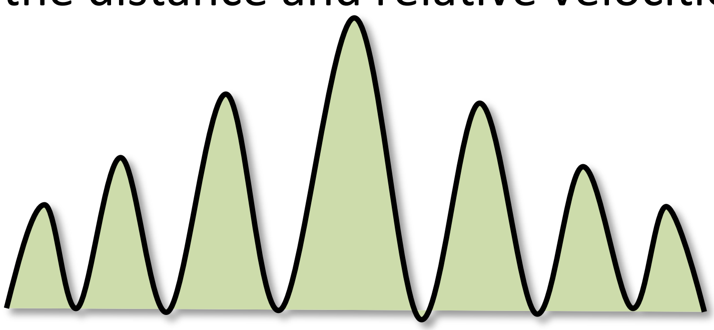
- In Binary Phase Shift Keying (BPSK), a form of PM, transitions in a single input data stream (0-to-1 or 1-to-0) cause 180° phase shifts in the RF carrier when a single data channel is being modulated.
- Extending this concept, two data channels can be modulated onto a single RF carrier using Quadrature Phase Shift Keying (QPSK) modulation. This form of phase modulation causes phase shifts of 90° to 180° in the RF carrier, depending on whether the data channels happen to shift simultaneously (or not). In some cases, the phase shifts for each channel are offset by ½ a phase – this is known as Staggered QPSK (SQPSK) or Offset QPSK (OQPSK).

The ACE satellite BPSK modulates its downlink with a single data channel. This physical channel actually contains numerous time-multiplexed virtual data channels.

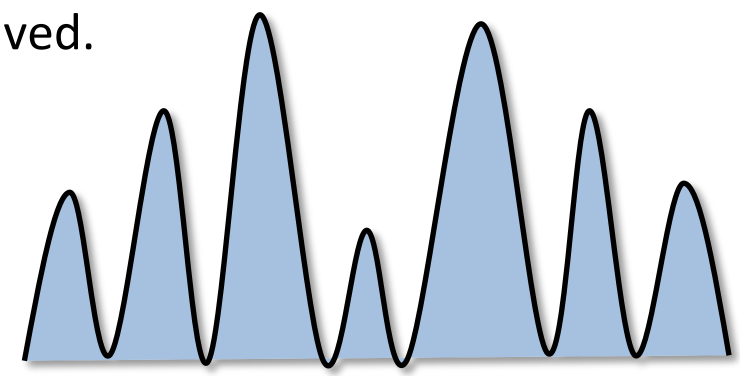


Modulation Index

- Modulation Index is a measure of the degree to which the RF carrier signal has been modulated – how transmitter power has been divided between the data channel(s) and the RF carrier
- In a high modulation index transmission, more power is allocated to the data channel than the carrier. A low mod index means that the carrier gets more of the transmit power
- High mod results in better signal-to-noise ratio (SNR) on the data channel, but it may make it more difficult for the receiving station to lock to the carrier
- Low mod assists the receiving station in locking onto the carrier but at possible expense of lower data channel SNR. This compromise is often necessary for interplanetary missions where achieving carrier lock is a big challenge due to the distance and relative velocities involved.



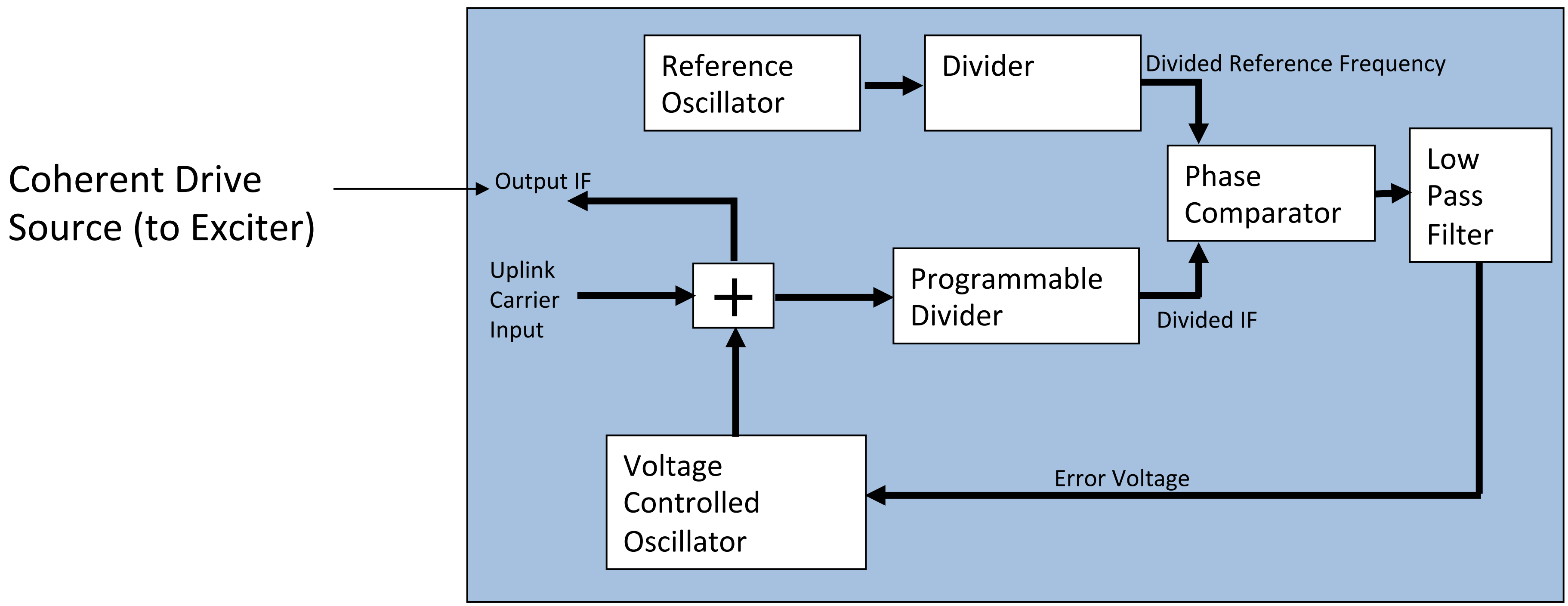
Modulated Signal



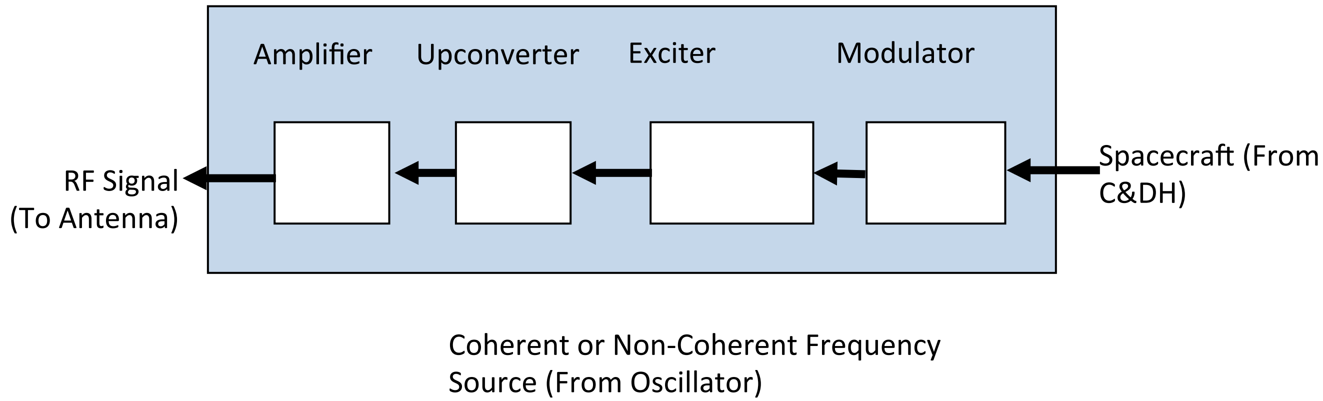
Suppressed carrier Modulated signal

Transponder Coherent Mode

- When a transponder is configured for coherent operations, the downlink carrier frequency is derived from the uplink frequency at a specific ratio (known as the "turnaround" ratio) and is phase coherent to the uplink. Phase coherent means that the downlink carrier phase is synchronized with the received phase of the uplink carrier.



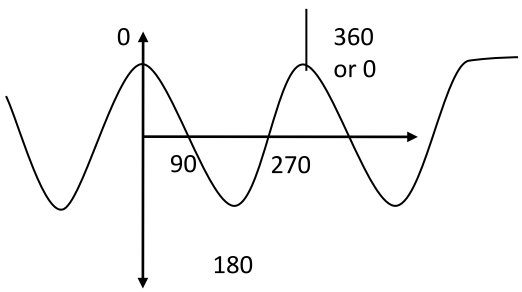
Transponder – Transmitter – Amplifier



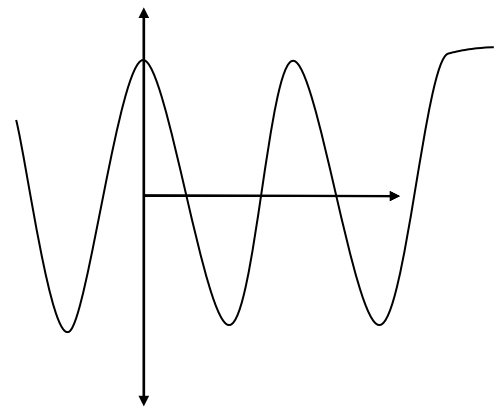
- Amplifiers boost the power of the modulated RF signal to a level sufficient (under predicted conditions) to survive the transmission path journey – and result in successful reception of the signal at the other end of the RF link.
- Two kinds of amplifiers are used in transponders:
  - <u>Traveling Wave Tube Amplifiers (TWTA)</u> – extensive flight heritage; best amplifiers for high power/high frequency applications.
  - <u>Solid State Power Amplifiers (SSPA)</u> – newer, smaller, lighter; becoming the amplifier of choice for low to medium power/frequency applications (up to 40W at UHF, 30W at S-Band and 25W at X-Band).

Electromagnetic Wave Amplification

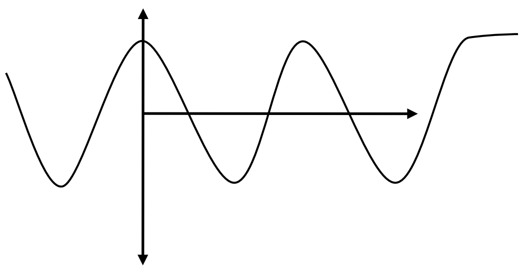
Sine wave



Phase - Fraction of a complete wave cycle



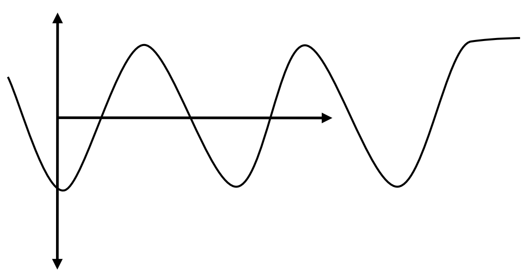
Sine wave in phase



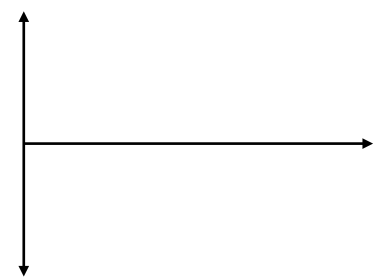
Two waves are in phase if their oscillations are in sync.

Combining the waves that are in phase will result in a stronger wave, i.e., increases amplitude.

Sine wave phase shifted by 180 degrees



Two waves are offset in phase if their oscillations are not in sync.

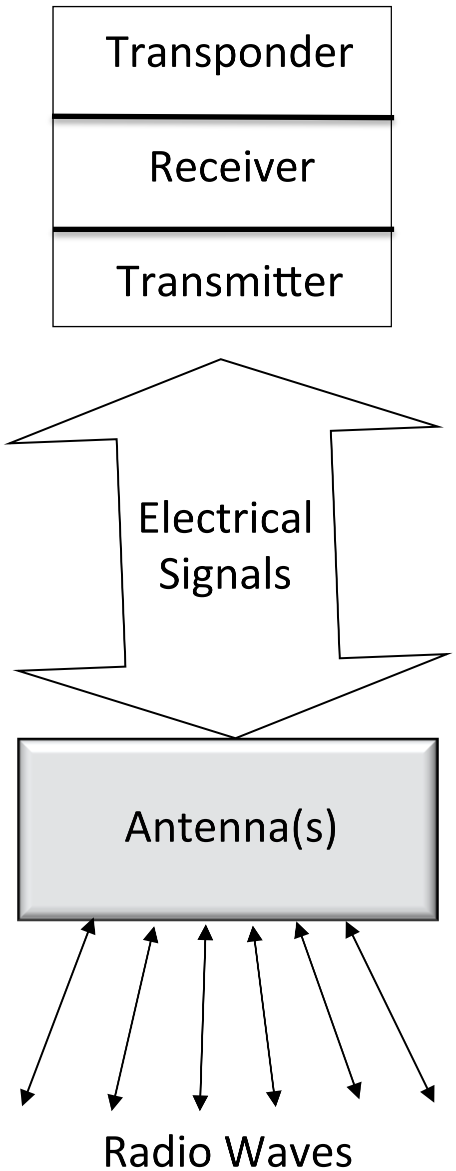


The waves arriving at the antenna, are collected in phase and if the reflection/ focus from the antenna keeps them in phase the result is a stronger signal!

Combining two waves that are 180 degrees out of phase results in them cancelling each other out.

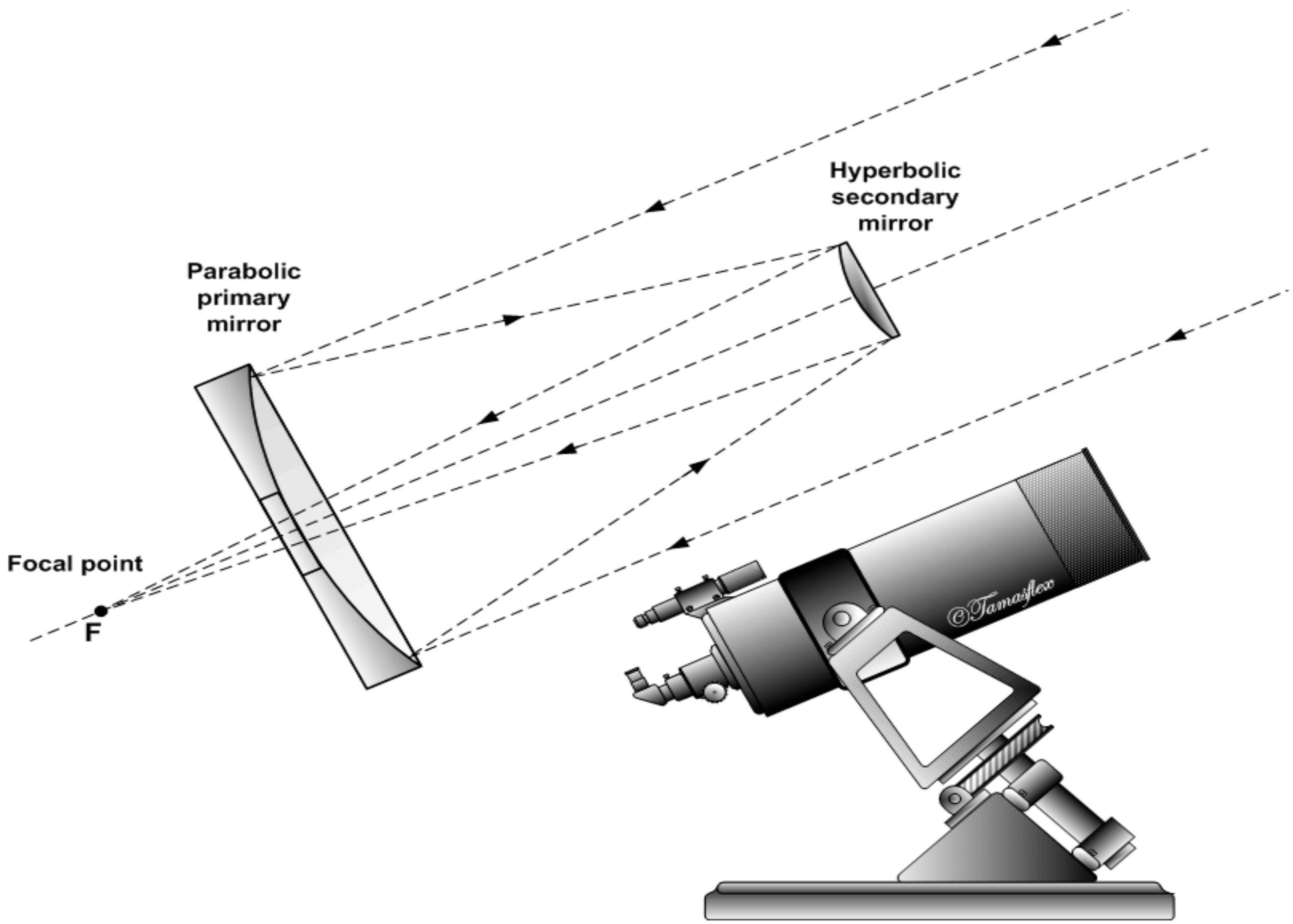
Question: What if the two waves are 90 degrees out of phase?

Antenna Purpose



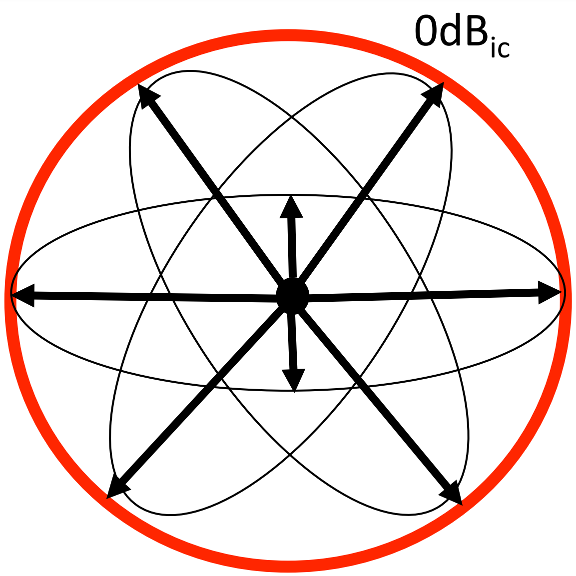
Focusing an EM Source

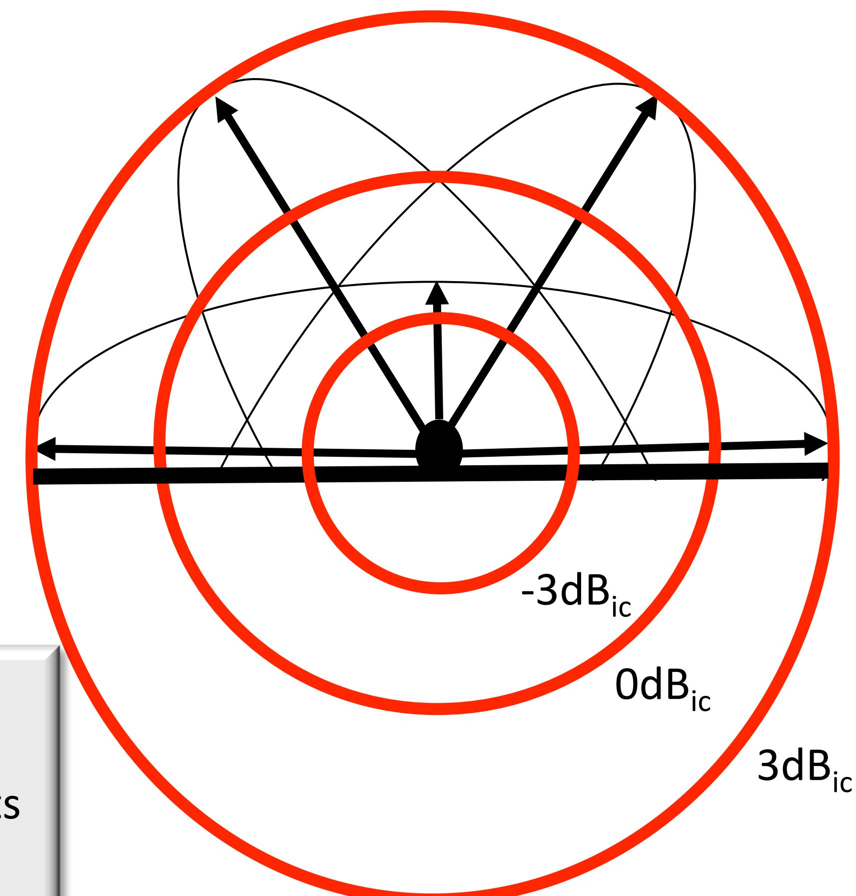
Basic principle of collecting desired signals- i.e. How parabolic antennas work.



Antenna Operation: Gaines & Losses

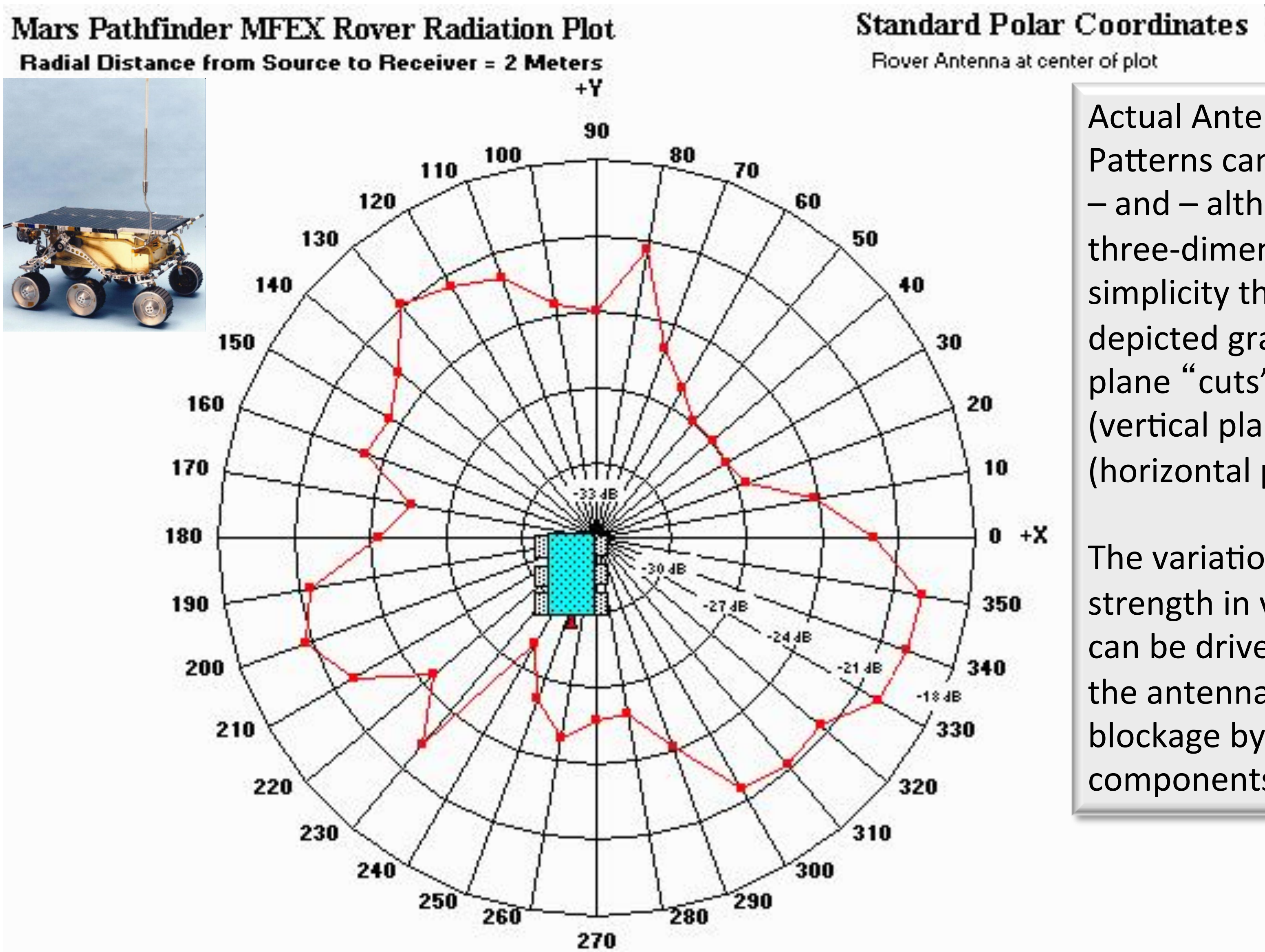
When compared with an isotropic antenna - all real antennas have stronger/weaker signal strength in various directions – referred to as “gains” and “losses” from the isotropic antenna – measured in dB_{ic} where the “ic” refers to “isotropic”.





An antenna that radiates/receives equal signal strength in all directions (radiation pattern a perfect sphere) is an <u>isotropic antenna</u>. It exists only in theory but it is valuable for comparison for measuring the performance of real antenna.

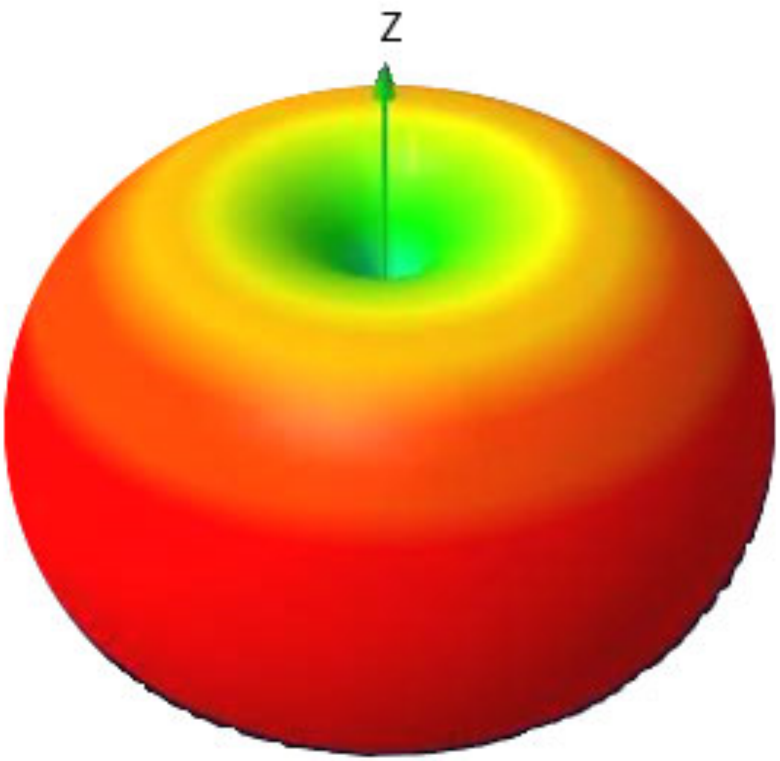
Antenna Operation: Radiation Patterns

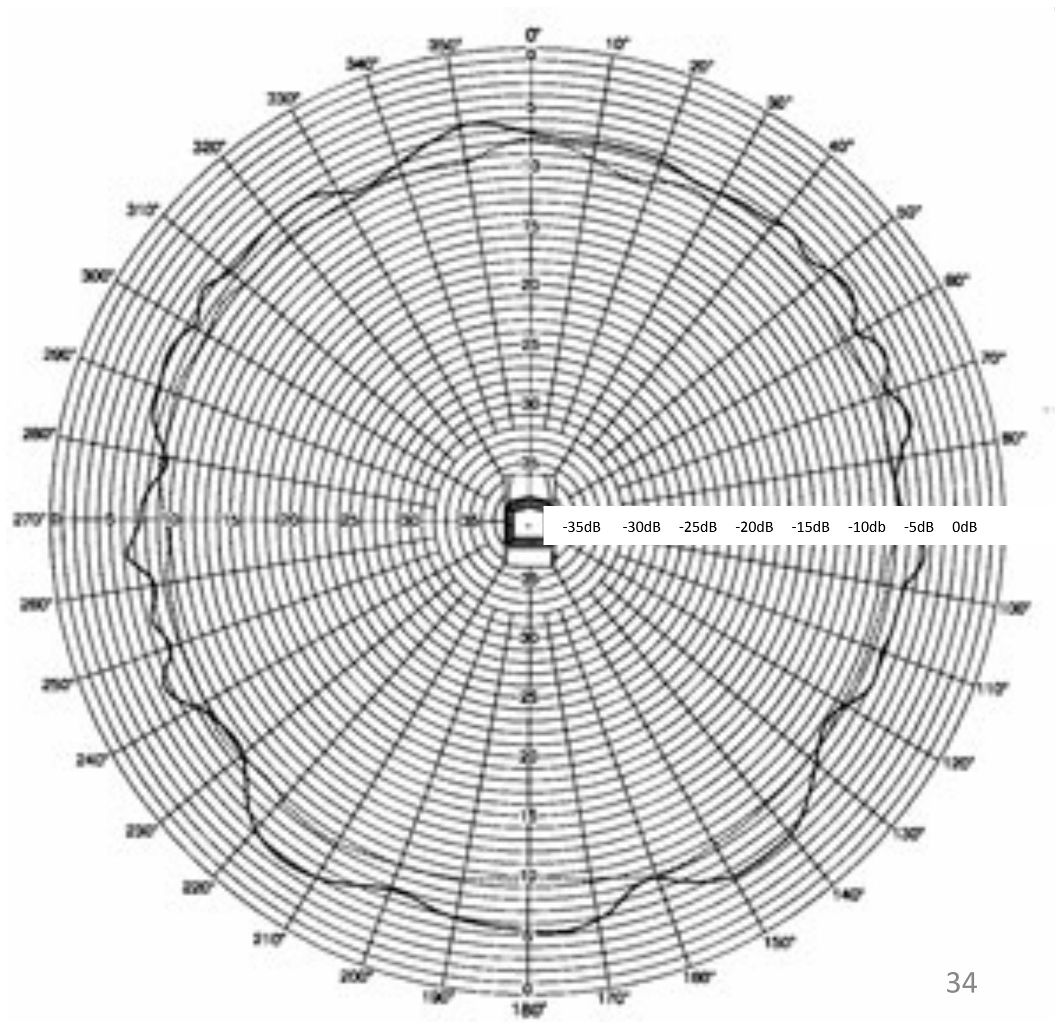


Actual Antenna Radiation Patterns can be very complex – and – although they are three-dimensional – for simplicity they are typically depicted graphically in single plane "cuts" – elevation (vertical plane) and azimuth (horizontal plane).

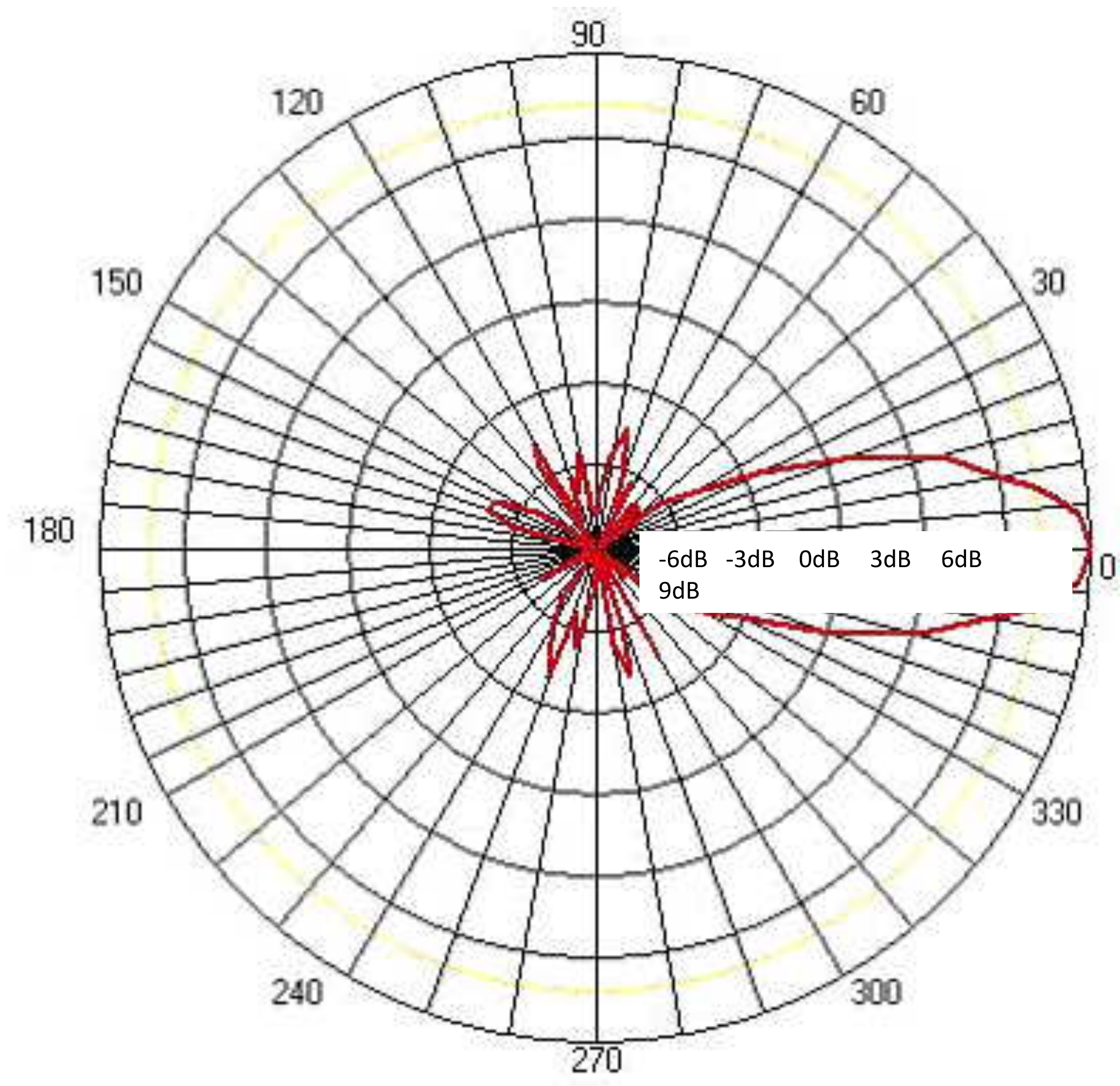
The variation in signal strength in various directions can be driven by the design of the antenna and antenna blockage by other spacecraft components.

Omni-Directional Antennas



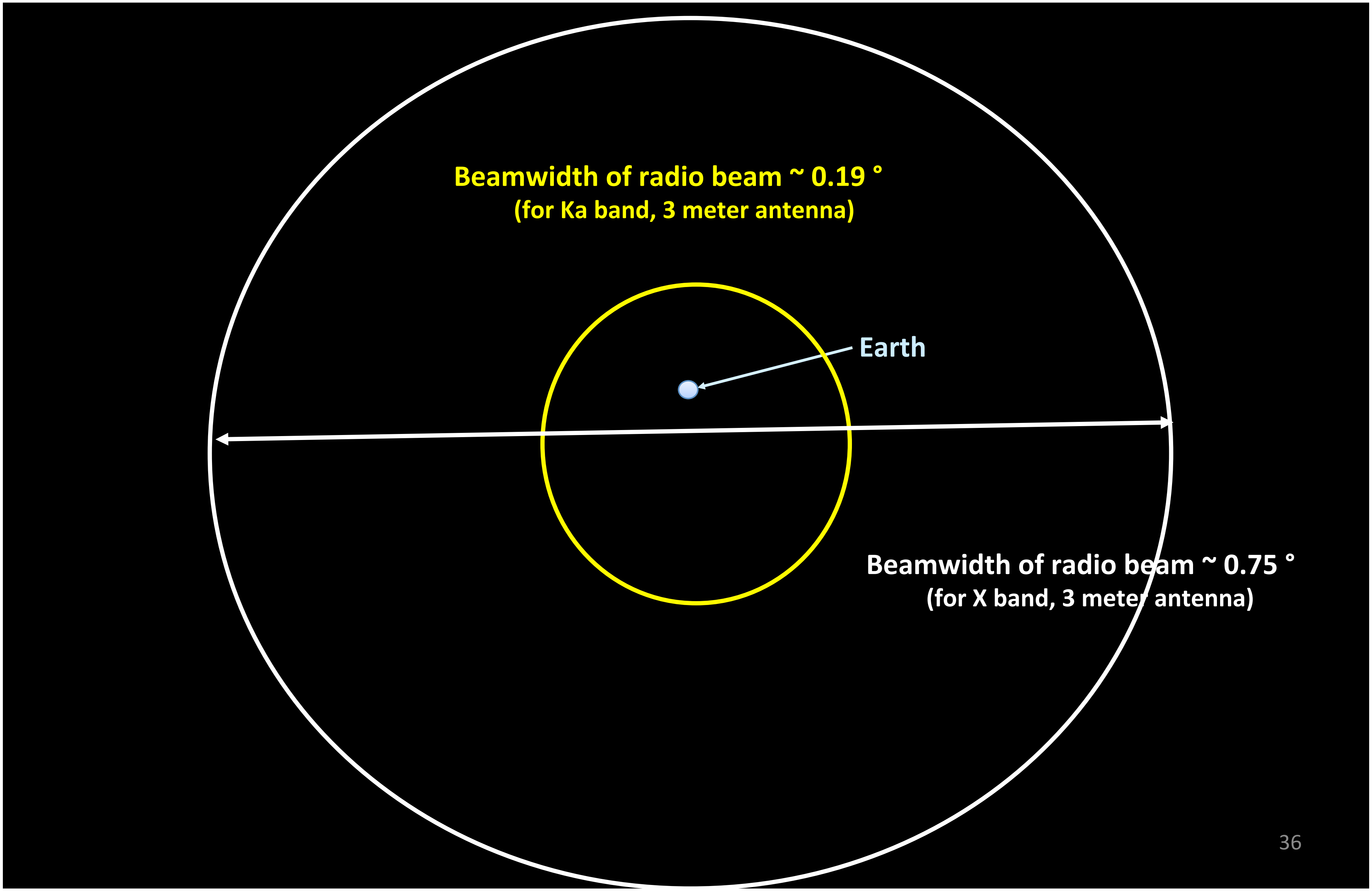


Directional Antennas

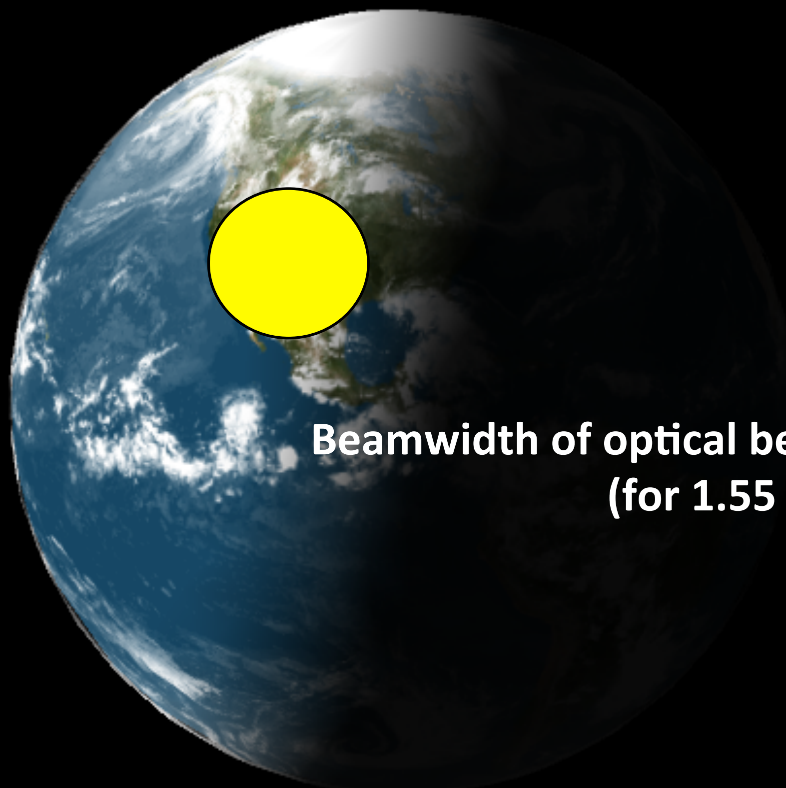


Some antennas are designed to focus energy in a specific direction – these “directional antennas” - also known as “high gain” antennas - typically produce gains significantly above the isotropic standard – but – only over a narrow area – while in most other directions – these antennas have very low gain/high losses.

Beamwidth Example: Radio from Mars



Beamwidth Example: Optical from Mars



A much larger percentage of transmitted energy goes into the receiver However the losses are greater and the current electronics are not very efficient. However, there is positive advantage over RF

Antenna Design: Calculating Gain

Where:

- η = antenna efficiency
- λ = wavelength (m)
- A = antenna aperture (m^2)

$$\text{Antenna Gain} = 10\text{Log}[\eta(4\pi/\lambda^2)A]$$

Taking the log of the answer and multiplying by 10 converts the answer to decibels.

Although this equation is shown with wavelength, you could use the signal frequency

Where:

- C = 3x108 m/s (speed of light)
- F = frequency (Hz)

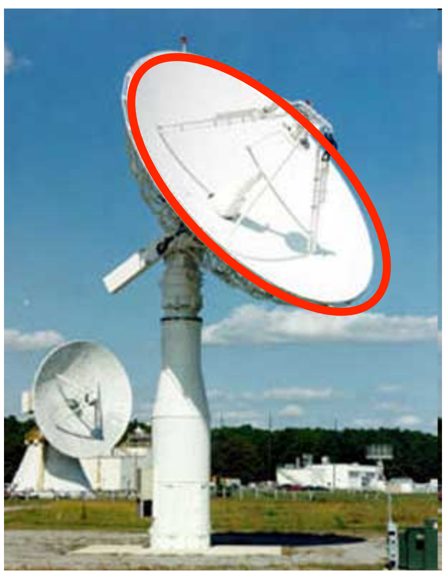
$$(\lambda=c/f)$$

Note: While the size of the antenna effects the gain, the wavelength also contributes to the gain. i.e. the smaller the wavelength (higher frequency) higher the gain!

Antenna Design: Calculating Aperture

Antenna Gain = $10\text{Log}[\eta(4\pi/\lambda^2)A]$

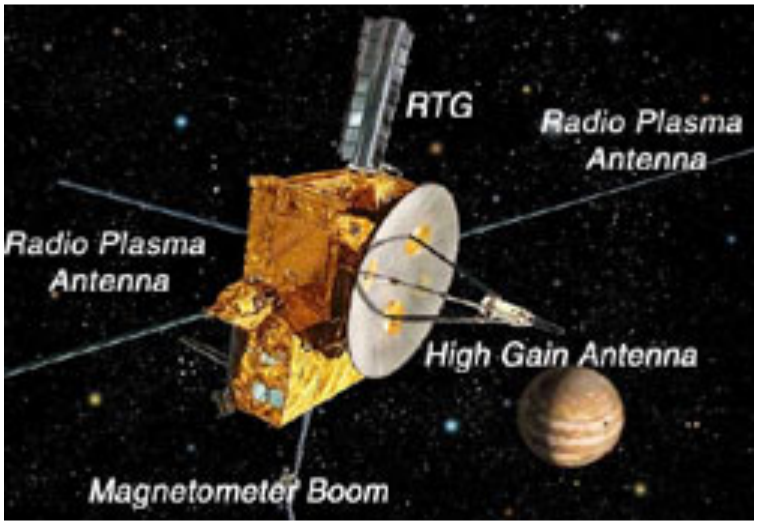
- Most antennas have a physical aperture – or – opening – through which they gather/transmit RF energy.
- Antenna aperture is always reduced to some degree by antenna losses such as the effective aperture is less than the physical aperture.
- But for now, for simplicity, we will ignore such losses (the efficiency parameter in the gain equation will be used to account for these losses).



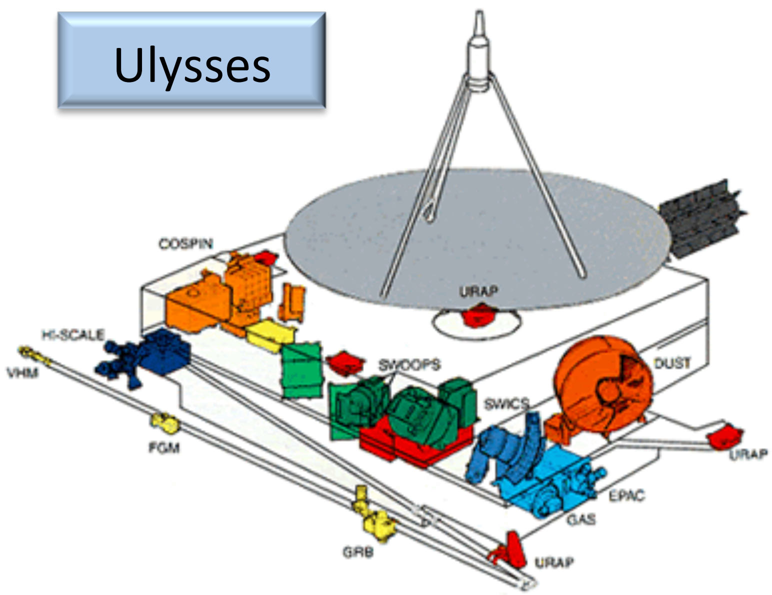
$A = \pi D^2/4$
(for a dish antenna)

$A = S1 \times S2$
(for a horn antenna)

Spacecraft Antenna Types: Monopoles

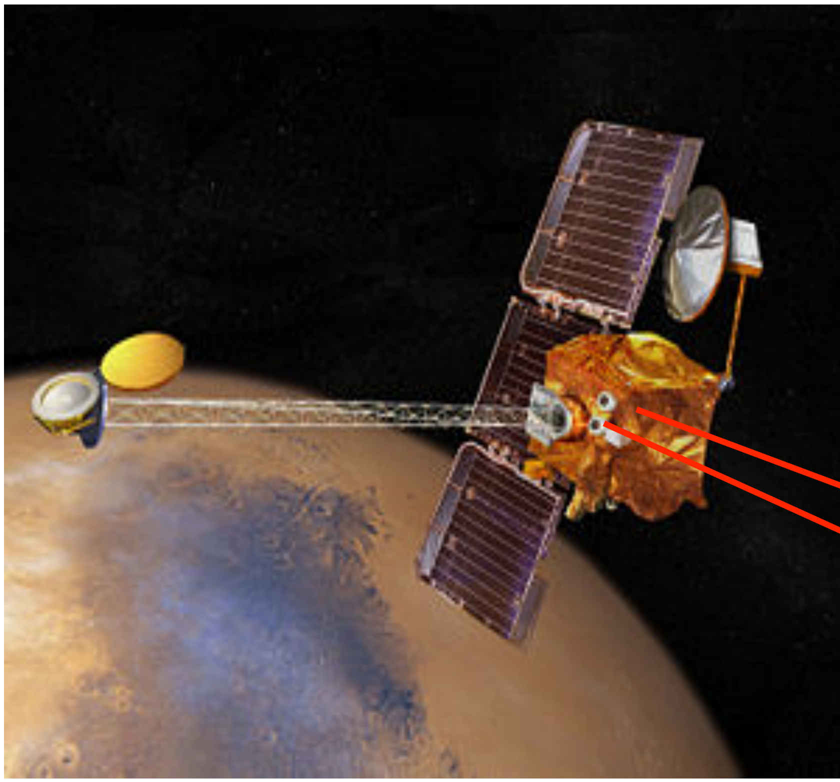


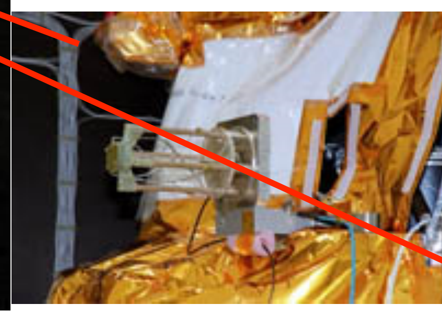
Ulysses

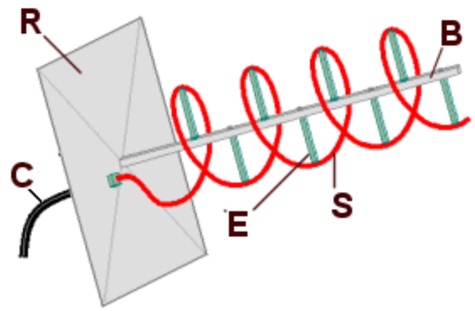


- Ulysses was reliable, radiation-resistant, spin stabilized spacecraft
- 1.65 meter, Earth-pointing high-gain antenna that provides the communications link
- A pair of monopole wire boom antennas with a combined length of 72 meters, extended outward perpendicular to the spin axis and a single 75 meter monopole axial boom antenna protrudes along the spin axis opposite the high gain antenna to form a long, three-axis radio wave/plasma wave antenna

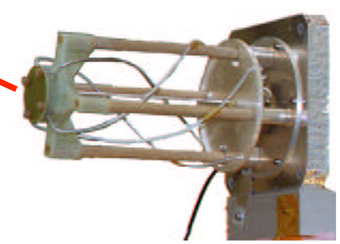
Spacecraft Antenna Types: Helix





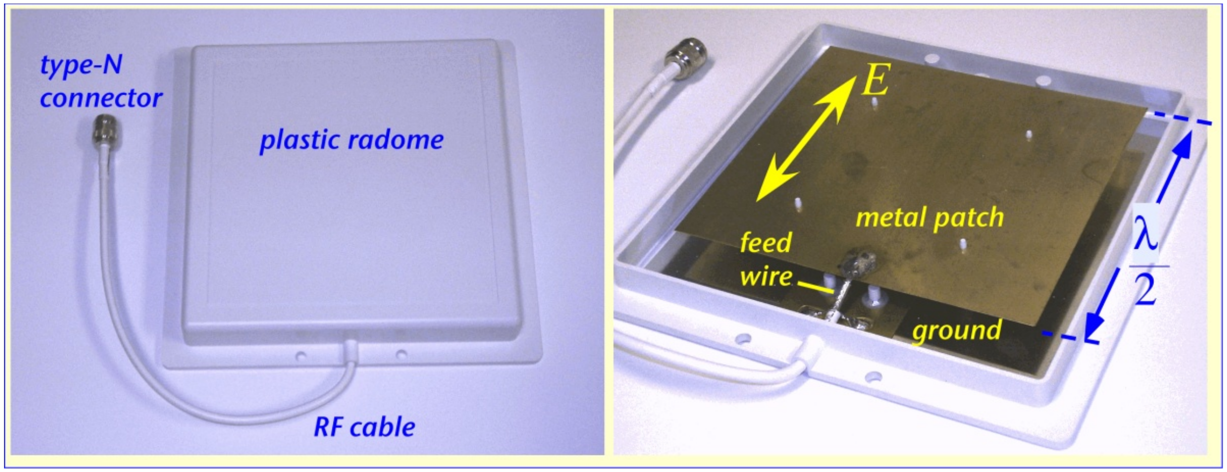


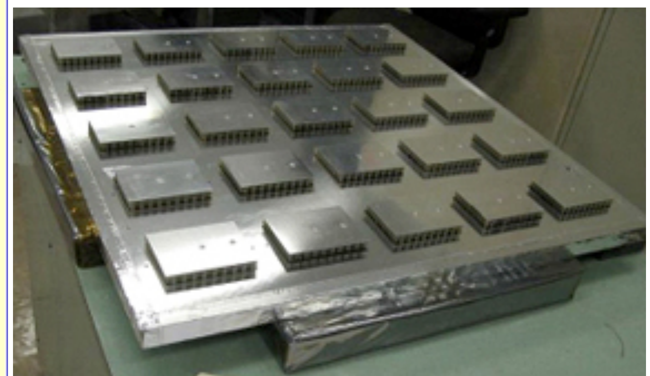
B: Central Support,
C: Coaxial Cable,
E: Spacers/Supports for the Helix,
R: Reflector/Base,
S: Helical Aerial Element



The Odyssey spacecraft helix antenna design radiating at 90 degrees from the vertical or horizontal plane is efficient as a practical reduced-length radiator when compared with the operation of other types such as base-loaded, top-loaded or center-loaded whips. They are typically used for applications where reduced size is a critical operational factor.

Spacecraft Antenna Types: Patch

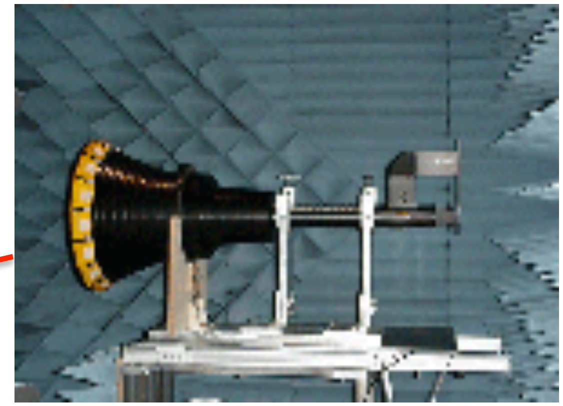




- A patch antenna (also known as a Rectangular Microstrip Antenna) is a popular type. Its name is attributed to the fact that it usually consists of a single metal patch suspended over a ground plane. The assembly is usually contained inside a plastic radome to protects the structure from damage. Patch antennas are simple to fabricate and easy to modify and customize.
- The radiation mechanism arises from discontinuities at each truncated edge of the microstrip transmission line. Radiation at edges causes the antenna to be slightly larger than its physical dimension electrically. In order to obtain a resonant condition at the antenna driving point, a shorter than a one-half wavelength section of microstrip transmission line is used.

Spacecraft Antenna Types: Horn

Intelsat-901

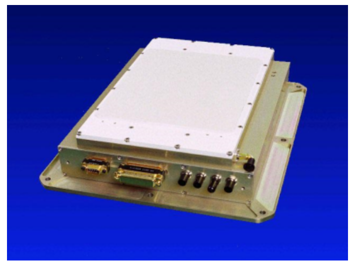


4 GHz Horn Antenna

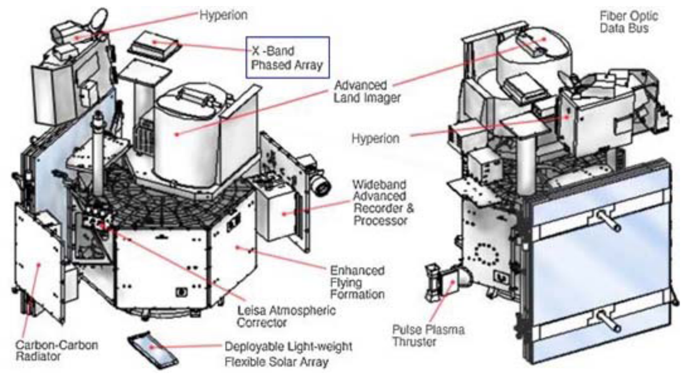
- In satellite dish and antenna design, a feedhorn is a horn antenna used to convey radio waves between the transceiver and reflector. The feedhorn also selects the polarity of the waves to be received, which helps to attenuate unwanted signals from adjacent transponders and from other communication satellites at nearby orbital positions.

Spacecraft Antenna Types: Flat Panel

EO-1 Satellite



X-band Phased Array Antenna (XPAA)



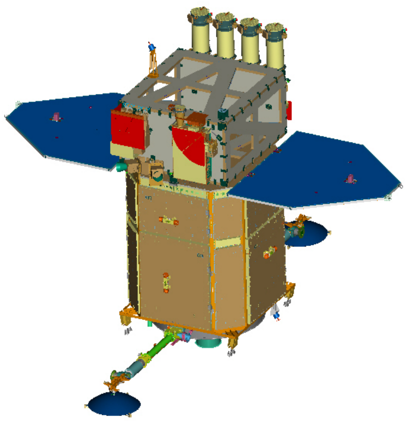
Exploded view of EO-1 spacecraft indicating the location of the XPAA at the end of a boom on the nadir-facing panel.

- Earth Observing-1 demonstrated high data rate, low mass X-band Phased Array Antenna (XPAA) for returning to ground the imaging data stored in solid-state recorder. XPAA combines the functions of antenna, 2-axis gimbal, gimbal controller, and solid-state power amplifier (SSPA) in a single, low-cost package.

- Phased array technology offers significant benefits over mechanically pointed parabolic antennas, including the elimination of deployable structures, moving parts, and their torque disturbances.

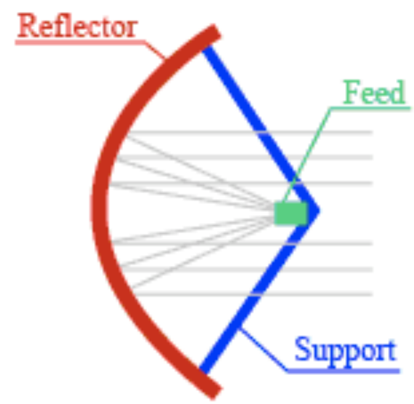
- The division of the SSPA function into 64 individual element amplifiers enhances the reliability and fault tolerance of the X-band downlink system.

Spacecraft Antenna Types: Parabolic Reflector



SDO Ka-band Reflector antennas

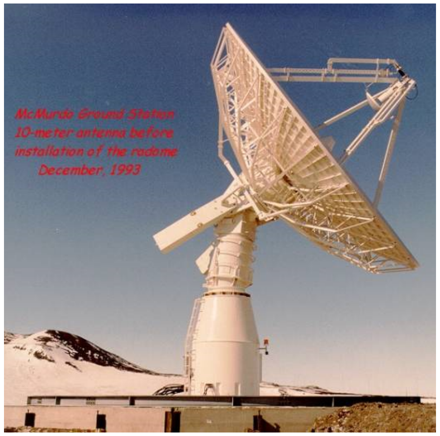
SDO Ka-band Reflector antenna development

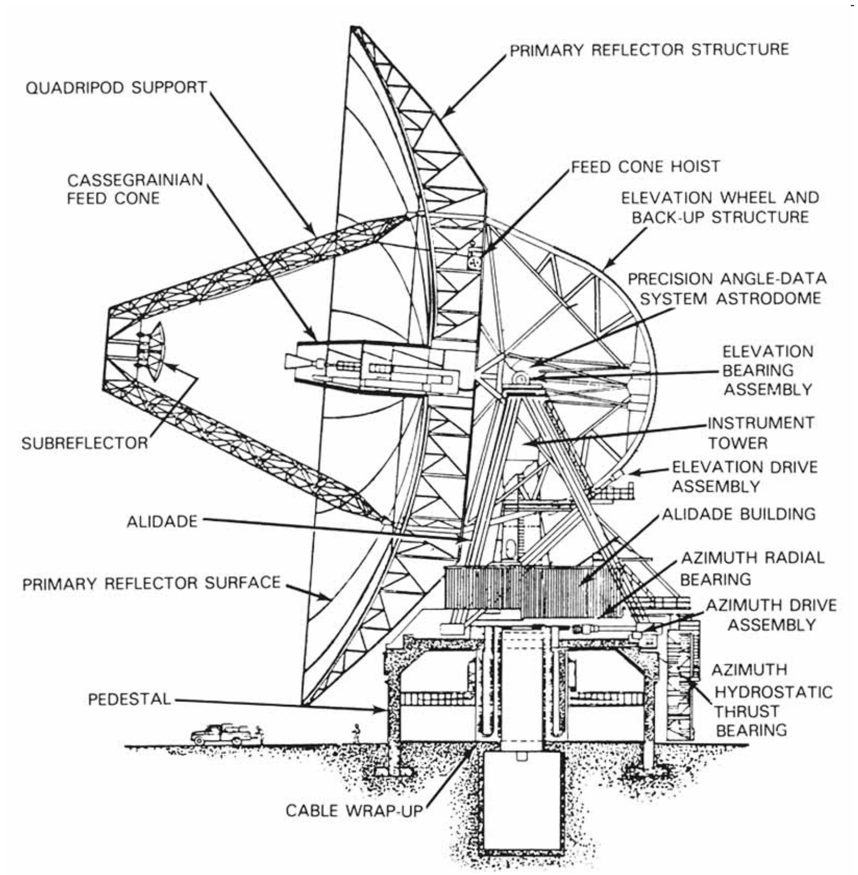


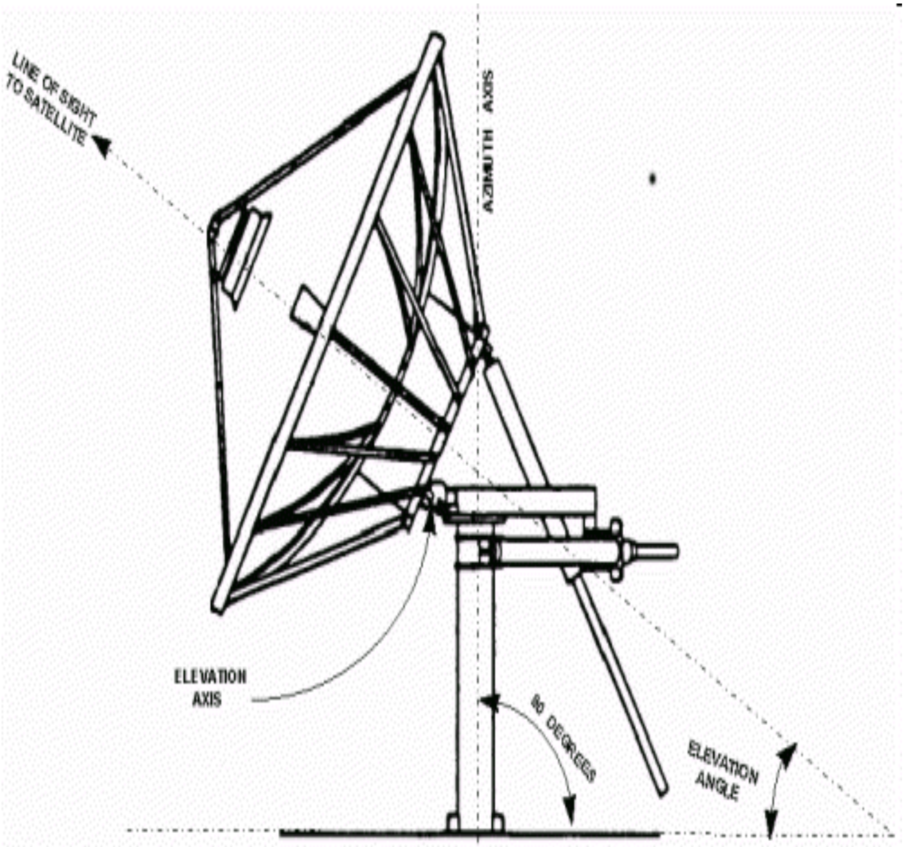
Parabolic

- The most well-known reflector antenna is the parabolic reflector antenna, commonly known as a satellite dish antenna.
- Typically have a very high gain (30-40 dB is common) and low cross polarization.
- Axially symmetric dual reflector antenna in a Cassegrain configuration, using a primary and secondary reflector. A conical corrugated feed horn is mounted at the base of the primary reflector. Energy fed to the horn radiates to the secondary reflector which illuminates the primary reflector. The main radiation beam of the antenna is then formed predominantly by the energy distribution on the primary reflector, plus spillover from the reflectors.

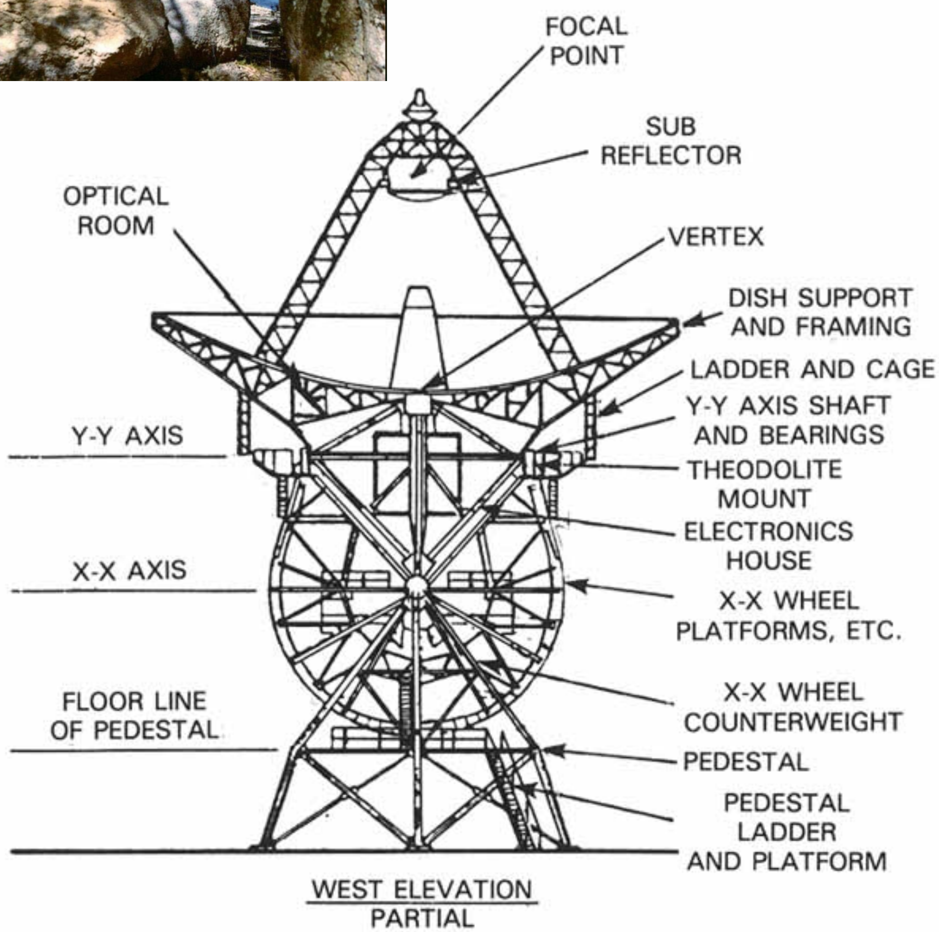
Ground Antenna
AZ-EL Mount

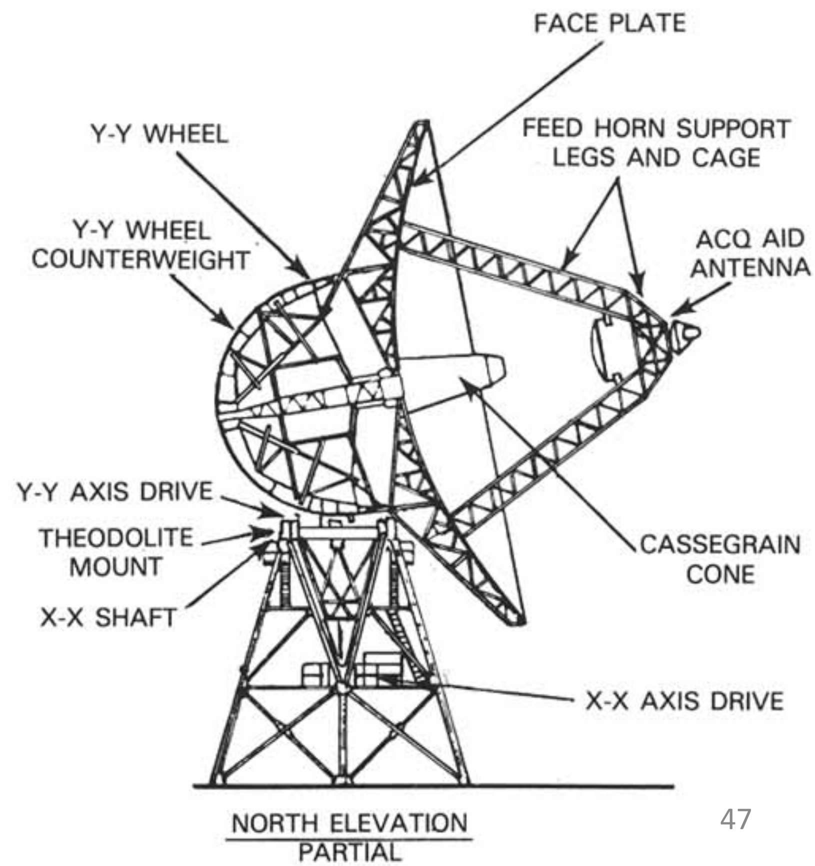






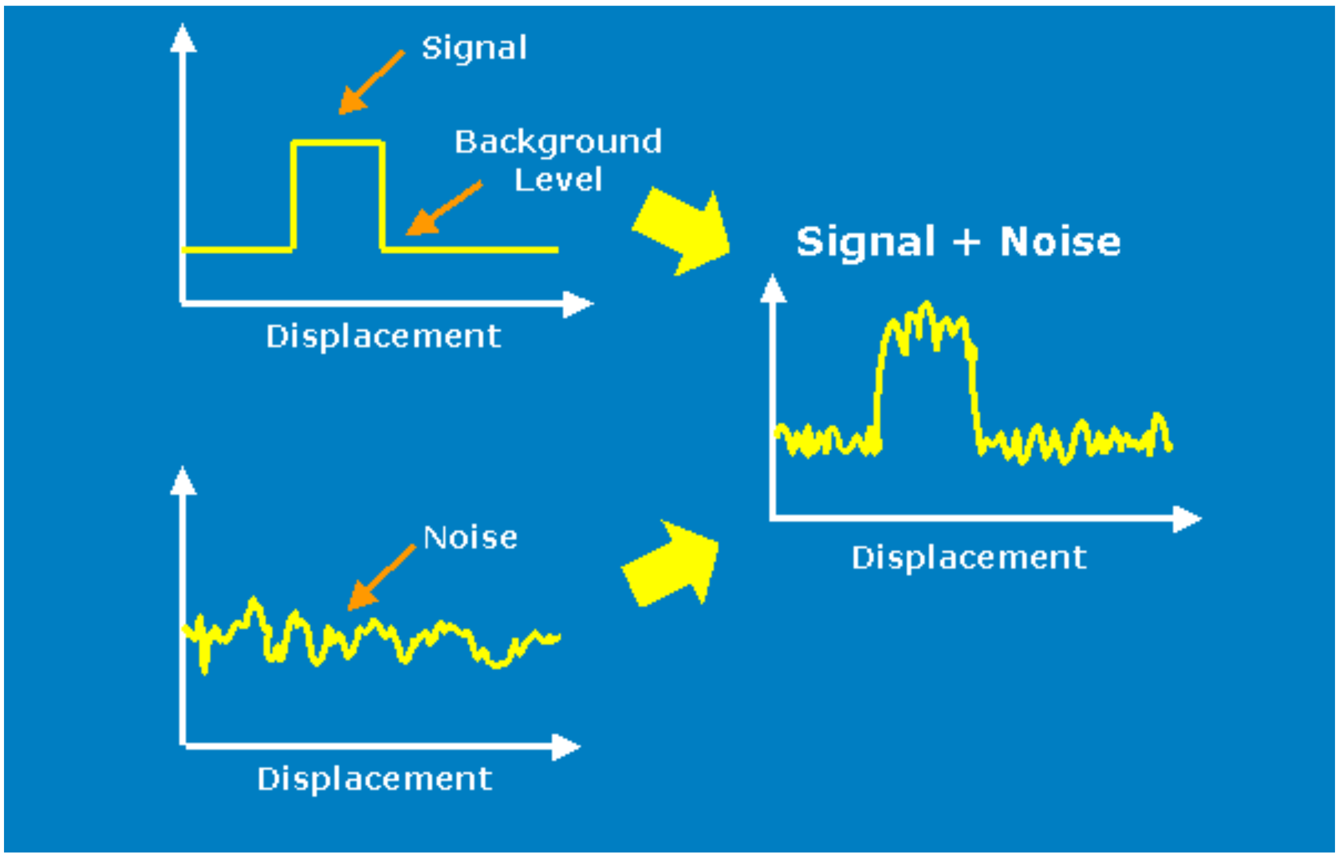
Ground Antenna
X-Y Mount





Signal-to-Noise

The relationship between the signal strength and the noise strength is expressed as the Signal-to-Noise Ratio (SNR). The greater the ratio between signal and noise – the higher the SNR value – the better the chances of successful signal acquisition.



A number of receiver components – amplifiers, filters, limiters – are in the receiver specifically to isolate the desired signal from the noise that is inherently present in the received signal.

Link Budget Analysis

- Link Budget Analysis can be performed for both the downlink and uplink, but the parameters used in the calculation will vary. Factors which must be considered include:
  - Uplink power amplifier gain and noise factors
  - Transmit antenna gain
  - Slant range and corresponding atmospheric loss over distance
  - Satellite transponder noise levels and power gains
  - Receiver antenna and amplifier gains and noise factors
  - Cable losses
  - Adjacent satellite interference levels
  - Climatic attenuation factors
- The end product of a link budget analysis is a "link margin" – the difference between calculated signal-to-noise ratio and required signal-to-noise ratio.
- Signal-to-noise ratio is the ratio of received energy/but to the noise density – basically how "noisy" is the received signal?

Link Margin

Signal-to-Noise Ratio

$$\text{Link Margin} = (E_b/N_0)_c - (E_b/N_0)_r + I$$

$$E_b/N_0 = EIRP + L_s + L_a + G_r - 10\log T_s + 228.6 - 10\log R$$

- E_b Received energy/bit
- N_0 Received noise density
- $(E_b/N_0)_c$ Calculated signal-to-noise ratio (dB_w)
- $(E_b/N_0)_r$ Required signal-to-noise ratio
- EIRP Effective Isotropic Radiated Power (dB_w)
- L_s Free space loss (dB_w)
- L_a Atmospheric path loss (dB_w)
- G_r Receive antenna gain (dB_w)
- T_s System noise temperature (K)
- R Data rate (bps)
- I Implementation loss

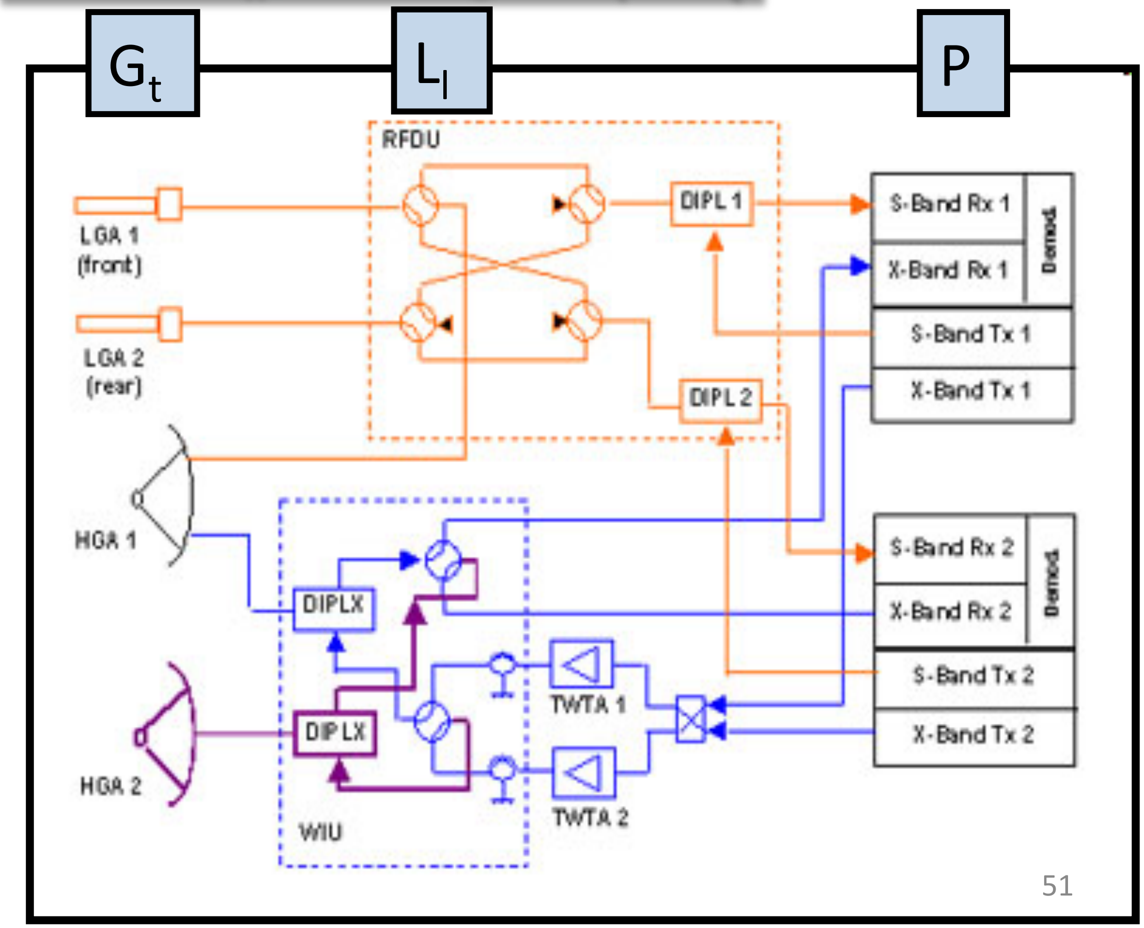
Effective Isotropic Radiated Power

$$E_b/N_0 = EIRP + L_s + L_a + G_r - 10\log T_s + 228.6 - 10\log R$$

$$EIRP\ (dB_w) = 10\log P + L_l + G_t$$

EIRP is calculated by combining:

- Output RF power of the transmitter, P, (W)
- Signal losses incurred between the transmitter and the antenna, L_l, (dB_w)
- Gain of the transmit antenna relative to an isotropic antenna, $G_{t,}$ (dB_{ic})



Free Space Loss

$$E_b/N_0 = EIRP + L_s + L_a + G_r - 10\log T_s + 228.6 - 10\log R$$

During the transit between the transmit and receive antennas, the beam spreads out and weakens (otherwise known as attenuation) – this is the primary source loss in a communication link.

The equation for calculating Free Space Loss (L_S), is:

$$L_S = (c/4\pi Df)^2$$

L_S	Free Space Loss (W)
c	Speed-of-light ($3\text{x}10^8$m/s)
D	Complete distance between the transmitting and receiving antennas (m)
f	Frequency (Hz)

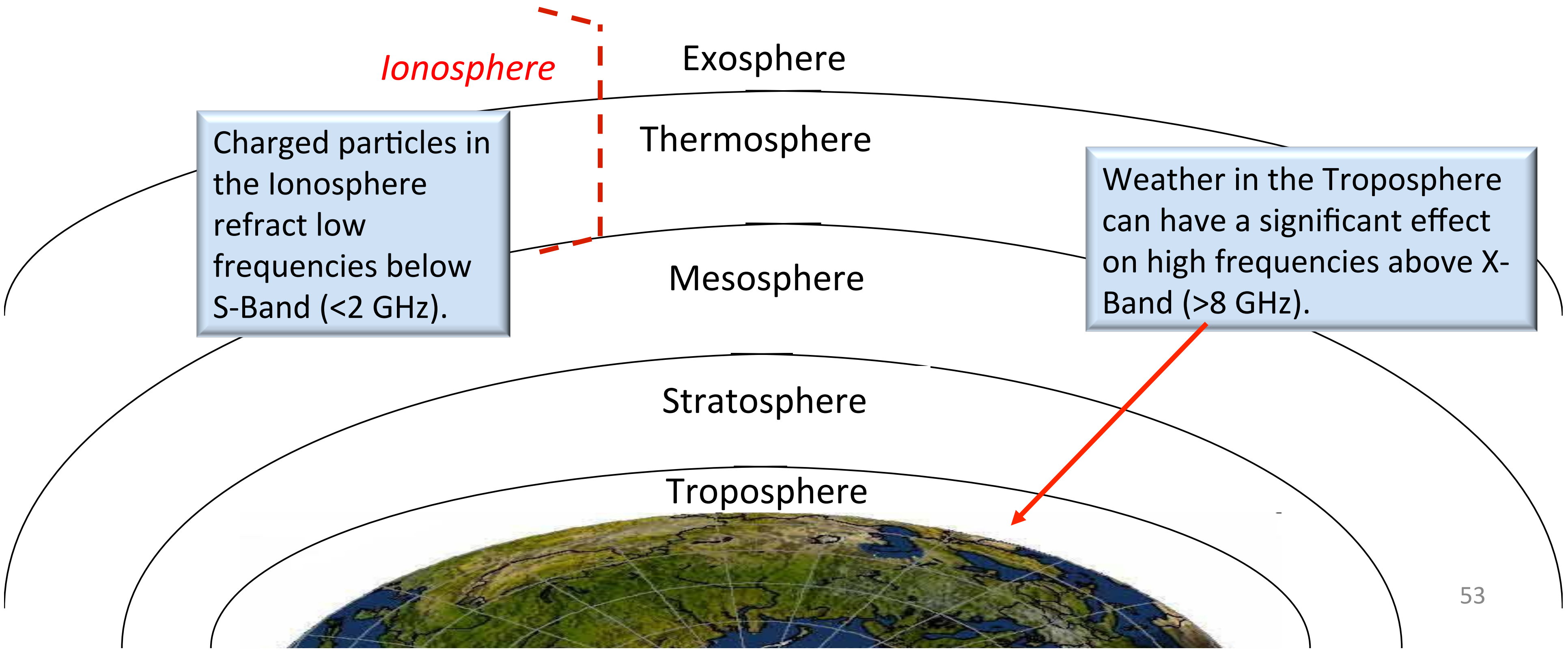
In the world of logs, this equates to:

$$L_S = 147.55 - 20\log D - 20\log f$$

Atmospheric Path Loss

$$E_b/N_0 = EIRP + L_s + L_a + G_r - 10\log T_s + 228.6 - 10\log R$$

- In addition to being attenuated during the long traverse between transmit and receive antennas, a signal encounters additional obstacles as it propagates through the Earth's atmosphere. These variable losses include the effects of humidity and rain on the signal.



Signals Reception - Gains/Losses (G_r/T_s)

$$E_b/N_0 = EIRP + L_s + L_a + G_r - 10\log T_s + 228.6 - 10\log R$$

Now that the signal has completed the journey from the transmitting antenna to the receiving antenna, we must consider the gains and losses incurred at this antenna. This is the receiving end analogy to the transmitting EIRP and is commonly given as G/T

- G_r Receive antenna gain (dB_W) at the receive frequency
- T_s Total System Noise Temperature (K); combines all physical sources of noise at the receiving antenna

T_s is the equivalent noise temperature (measured in Kelvins); this parameter lumps together all physical sources of noise at the receiving antenna, including:

T_{ant} Noise received by the antenna and antenna induced noise

T_r Noise generated in the receiving system

- 228.6 Conversion constant that correlates temperature with energy

Pointing Loss

- Additional factor that results when the receive antenna boresight is not aligned with the boresight of the transmitting antenna (max power)

$$L_\theta = -12(e/\theta)^2$$

- In systems with a narrow beamwidth, small errors in pointing – which may be induced by ground wind gusts or spacecraft attitude stabilization errors can lead to reduced received signal strength
- The equation for calculating the gain reduction caused by the off-pointing of the two antennas is:

For example: When $\underline{e = \theta/2}$ the pointing loss is $\underline{3\ dB_W}$ since you have gone out a distance ½ the beamwidth from the antenna boresight which coincides with the half-power beamwdith angle.

L_θ Reduction in gain (dB_W) from the peak gain due to off-pointing
e Pointing error (º)
θ Receive antenna half-power beamwdith (º)

Receiver Noise Temperature (T_r)

- Receiver Noise Temperature (T_r) includes all sources of noise between the receiver output and the antenna.
- Sources of this noise include:
  - Transmission Lines and Filters: Related to the ratio of output to input power.
  - Low Noise Amplifier: Related to the temperature of the receiver.

Cryogenic cooling systems can increase the SNR, thus decreasing thermal noise. The DSN employees this strategy to help in their efforts to capture the weak signals of distant spacecraft.

Boltzmann Constant – 228.6

$$E_b/N_0 = EIRP + L_s + L_a + G_r - 10\log T_s + 228.6 - 10\log R$$

- Up until we discussed T_s, we were discussing the loss and gain of power.
- Ts (temperature of the system) is in the units of dB_K.
- We need a way to convert this temperature (K) related value – into an energy related value – SO –.
- Along comes the Boltzmann Constant (k) (1.38x10-23 J/K) which provides a tool for performing this conversion.
- To use this constant in the link budget calculation we must perform the following math:
  - $10\log(k) = 228.6\ dB_W/HzK$.

Data Rate

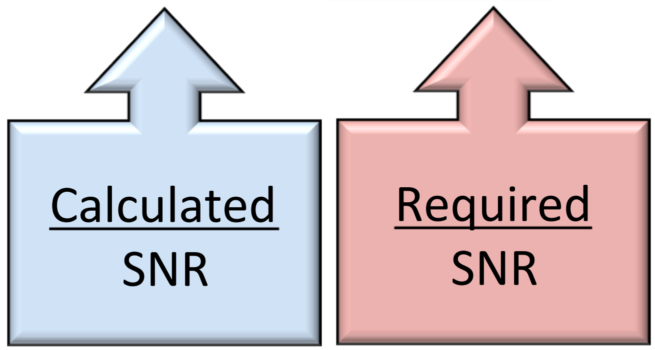
$$E_b/N_0 = EIRP + L_s + L_a + G_r - 10\log T_s + 228.6 - 10\log R$$

- Having followed the signal from its generation in the transmitter through the gains and losses incurred during transit and in the receiving system, the final step in determining the link budget is to address the data rate that needs to be supported (R (bps)) - bps = bits per second.
- Remember that the signal-to-noise ratio (E_b/N_0) is actually the ratio of received energy per bit to the noise density.
- R refers to what is commonly called the Symbol Rate which is the raw data rate, any header/trailer bits, plus all of the encoding bits. So - we are not just considering the data sent but any encoding or checksum overhead.

Required Signal-to-Noise Ratio

Now that we have examined the Calculated SNR portion of the Link Budget equation, we need to look at the Required SNR to determine if the Calculated SNR is adequate to meet mission needs.

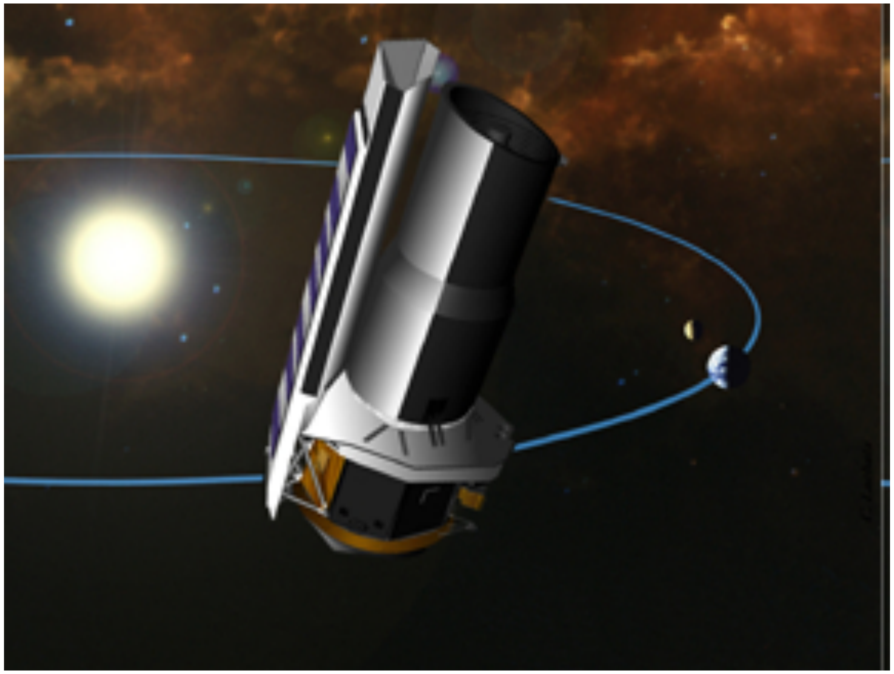
$$\text{Link Margin} = (E_b/N_0)_c - (E_b/N_0)_r + I$$



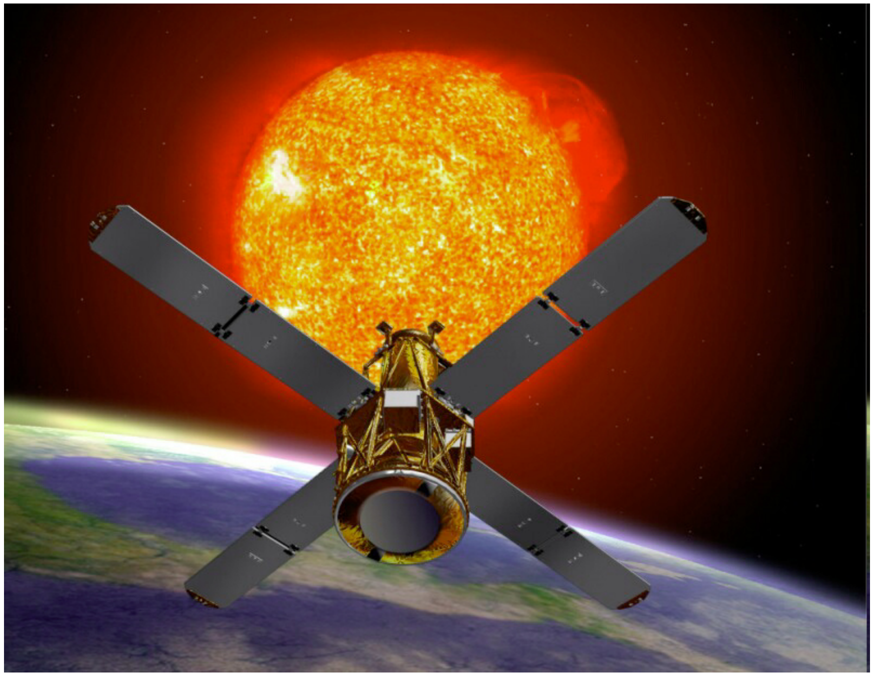
- The Required SNR is related to:
  - The maximum acceptable bit-error-rate (BER) that has been chosen for the mission.
  - The modulation scheme chosen (discussed previously).
  - The encoding scheme chosen (discussed previously).

Bit Error Rate

- The acceptable Bit-Error-Rate (BER) is the probability of receiving an erroneous bit.
- For example, a BER of 10^{-5} means that, on average, only one bit will be in error for every 10^{5} bits received.



The Spitzer Space Infrared Telescope Facility (SIRTF) has the following BER requirements:
Uplink: 10^{-5}
Downlink: 10^{-6}



The Ramaty High Energy Solar Spectroscopic Imager (HESSI) has the following BER requirements:
Uplink: 10^{-7}
Downlink: 10^{-5}

Coding Gain

- To reduce the BER for a given E_b/N_0, most mission use a Forward Error Correction (FEC) encoding scheme that can identify and correct numerous (although not all) bit errors.
- The primary disadvantage of encoding schemes is that they add additional bits (sometimes substantial numbers of bits) to the data stream.
- So – why incur the overhead of adding these additional bits to the data stream (and increasing the symbol rate – thereby reducing the $(E_b/N_0)_c$) – <u>Coding Gain</u> – that is, the probability that an error remains in the decoded data is usually much lower than if coding was not applied.
  - Example: A link that requires a BER of $<10^{-9}$ can achieve this goal with a given transmitter power and transmit/receive antenna gain with no encoding – or – by using encoding and getting the same BER with a lower transmitter power and/or lower antenna gains.
- The most popular encoding schemes, as discussed earlier, are:
  - Reed-Solomon
  - Convolutional
  - Turbo
  - Low Density Parity Check (LDPC)

How Much Margin is Enough?

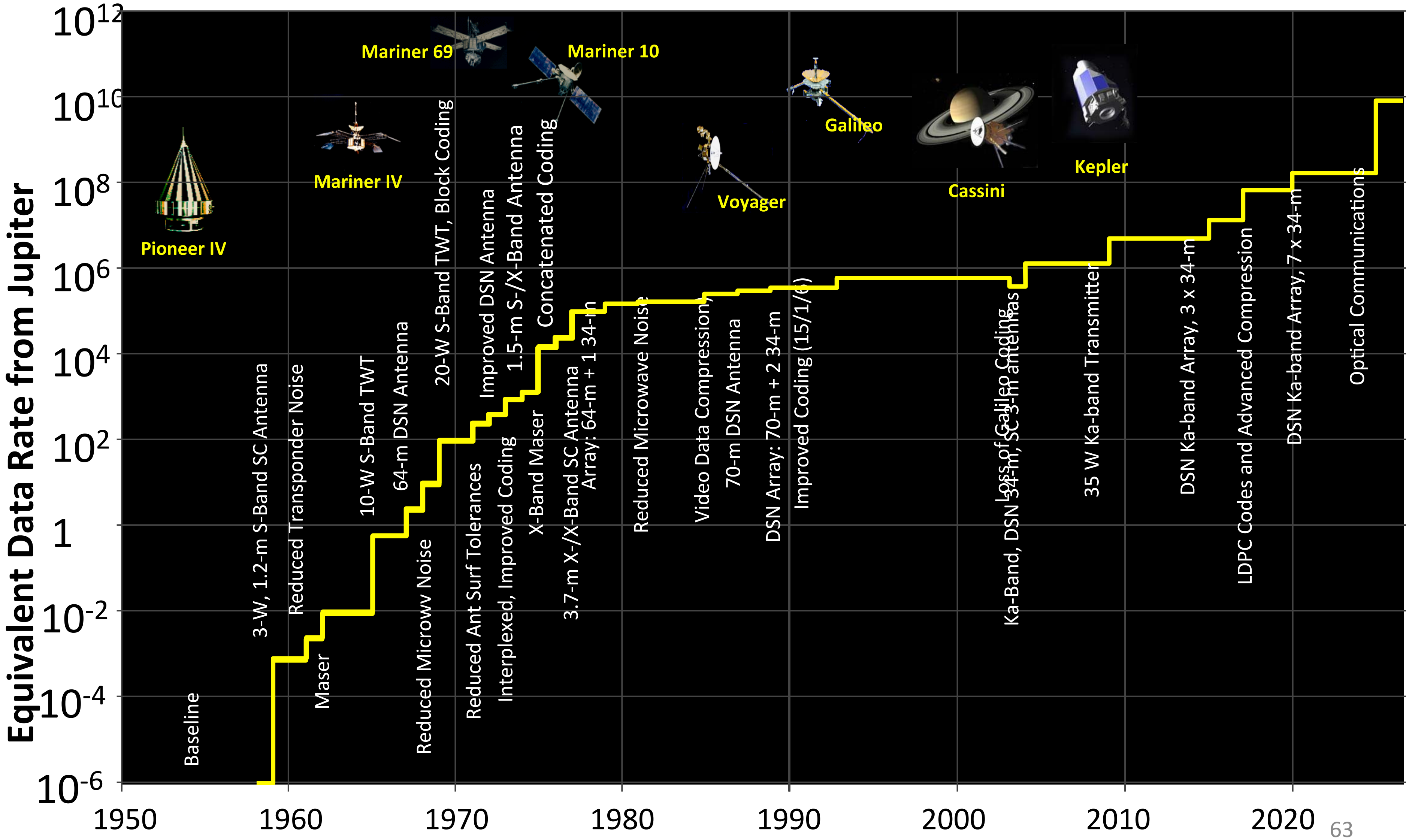
$$\boxed{\text{Link Margin} = (E_b/N_0)_c - (E_b/N_0)_r + I}$$

- Now that we have made our way through the link margin analysis, it is important to understand…

How much margin is "Enough"?

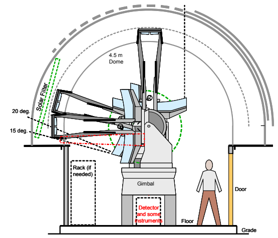
- On the one hand, too much margin is wasteful and costly.
- But – too little margin can result in an unacceptably high BER.
- So here are a few "rules of thumb":
  - At frequencies above 10GHz, the margin should be between 6-20 dBw to account for atmospheric and rain loss variations (you could be on the lower end of this spectrum if you have your ground terminal located somewhere that has minimal rainfall).
  - Frequencies in S, C, and X bands can usually get by with 3-5 dBw margins with the lower frequencies able to use lower margins.

Deep Space Telemetry

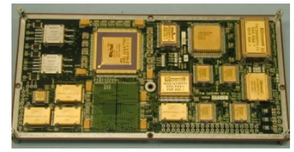


Optical Communications Technology

- **Develop optical technologies for 10-1200 Megabit per second data links to meet NASA SCaN requirements for 2020 IOC**
  - Low mass, high efficiency implementations are required for deep space optical link scenarios
  - Identify, develop, and validate high ROI ground and flight technologies
  - Create the necessary technical infrastructure to test and validate industry and NASA developed optical communications flight components prior to flight

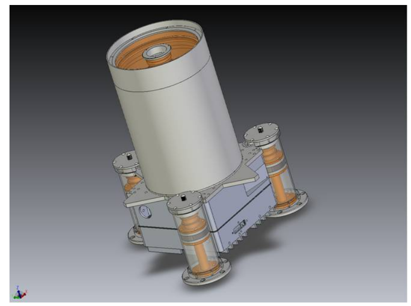


Ground Aperture

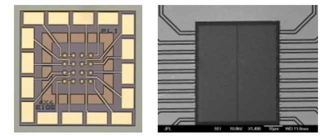


Optical Transceiver Flight Processor

PPM Laser Transmitter

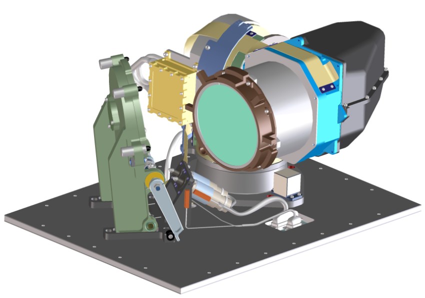


Deep Space Optical Transceiver



Single Photon Detectors

Scalable Receiver/Decoder



Near Earth Flight Terminal

Near Earth Ground Terminal

Some Example Key Challenges:

- Sub-Hertz vibration isolator; flight photon counting detector arrays
- Lightweight flight optics; integrated flight photon counting detector arrays with read-out integrated circuit
- Beaconless tracking solutions; high power uplink laser transmitter
- Detector jitter mitigation; efficient narrowband optical filter